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CONDITIONS AFFECTING STABILITY IN ELECTRIC LIGHTING CIRCUITS

BY ELIHU THOMSON

The term stability in this paper refers to that condition in which the current or potential, or both, remain at a steady value. Instability implies fluctuation which may arise from internal causes or be provoked by slight changes; and the fluctuations so arising may tend to be perpetuated automatically. An example of such action is the well-known " surging " in series arc-light circuits, which in the early days of development often became a difficulty.

The chief part of the present discussion will naturally have to do with the constant-current series circuits containing arc lamps operated by direct-current dynamos, by alternating-current transformers, by reactive devices in alternating-current circuits, or by rectified alternating currents from transformers. Much that will be touched upon is already well known; but there may be some matters which are not so well known, the bearing of which may be rendered more clear. The instability due to so-called " hunting " will be left out of present consideration, which will be confined chiefly to cases in which the load conditions themselves tend to instability.

The art of electric distribution began about 30 years ago with the direct-current series arc circuit. The load was inherently unstable owing to the peculiarity of the arc resistance falling with increase of current. This form of distribution seems destined to survive for a long period, especially for street service with the later luminous flame arcs of high economy. It will also hold its place in similar service with series incandescent lamps with metallic or other high economy filaments, the nature of the resistance of which results in stability of current. Such a circuit as the latter is therefore outside of present consideration. Where in fact the load in a circuit is of the nature of " dead " resistance, stability is assured, provided no other disturbing causes exist, such as speed fluctuations in driving the generators. This is of course the case in the incandescent lamp circuit, whether in series, in parallel, or in a combination of the two. In early continuous current plants of small capacity, it was, however, generally easy to note the disturbances introduced by speed irregularities, or even to count the revolutions of the driving engine, or to watch the intermittent action of the engine governor.

The coupling of machines in parallel, and the later introduction of turbine driving, have resulted in the almost complete elimination of such fluctuations and they may, therefore, be left out of consideration as having nothing to do with inherent lack of stability or with such instability inherent in the arrangement of the circuit itself. In passing, however, it may be remarked that sometimes in self-excited direct-current dynamos of constant-potential type, shunt or compound, the degree of sensitiveness to speed variations may be abnormal. This sensitiveness has occasionally been noted by designers in high-speed, high-efficiency machines of moderate capacity. In such cases each slight increment of speed raises the potential and immediately reacts to increase the field strength, in turn causing a further increase, and so on. With a slight fall of speed there is of course the opposite effect. The difficulty is exaggerated if the engine governor is a little late in making its compensations, and they are at their worst when the iron of the machine is worked at the steep part of the curve of magnetization much below incipient saturation. The remedy for this form of instability is an alteration of proportions in the design and the removal of mechanical accessory causes. By working higher up on the saturation curve the tendency to magnification of the effects above alluded to is much reduced. The greater stability secured is, of course, purchased at the cost of more copper or a less efficient field circuit, and in a compounded machine the curve of potential regulation may not be so flat.

It is fortunate that the great fall of resistance in carbon filaments occurs only at ranges of temperature much below normal incandescence, or such lamps might become a load tending to instability, as in the case of the Nernst glower, which requires the addition of devices for securing stability of current.

The metallic filament and metallized filament, having positive temperature coefficients, tend, if anything, to minimize all fluctuations, but the effect is naturally very small. Some tests made with rods of fairly pure silicon seem to show that, unlike carbon, it has a positive coefficient up to about 600° or 700° cent., beyond which the resistance falls very rapidly. Had, therefore, silicon possessed the refractory character of carbon, it would probably have been an unstable load, if otherwise suitable for filaments and tried in lamps.

The Nernst lamp glower is like the arc in being an unstable load. An arc started between electrodes held at a fixed distance apart and maintained at a constant potential difference would exemplify the most unstable condition possible, but the requirement is manifestly impracticable. It would result in infinite current passing. The current would grow in value until the assumed condition of constant potential difference ceased to exist. The condition reached would virtually be that of short-circuit. While the conditions assumed above are unrealizable, they are sufficiently approximated in practice, and they emphasize the fact of the need of some current-limiting or steadying device in circuit with the arc. Several arcs in series evidently do not change the nature of the problem. By an inspection of Fig. 1, in which the curves represent the relation of current and resistance and of current and potential in an open arc with fixed separation, these curves being properly regarded as "characteristics," the unstable condition is manifest. An enclosed arc gives substantially the same result.

It has been said with some truth that to design and construct a constant-potential dynamo that would work fairly well, was, even in the early years of the art, an easy undertaking compared with the production of a dynamo to operate a series of arc lights, involving a peculiar and little-known proportioning to secure stability of current in working a load so inherently unstable. The problem was not only this, but the stable current value had to be such as was proper to the machine, one which did not involve a destructive rise of temperature in the windings; and, on the other hand, one which was not so small in value as to involve such low temperatures in the windings as to indicate that the material was not being used at or near the maximum effectiveness.

It may be instructive to trace briefly the history of the development which preceded that of the constant-potential dynamo. Early in 1879 there existed arc machines working at about 10 amperes with a dozen or more arc lamps in series, the arc pressure being about 45 to 50 volts per lamp. The carbon-filament incandescent lamp was not brought out until about the beginning of 1880. It is well known that the original dynamos in service for arc lighting, excepting a small number of lighthouse plants, operated with the permanent magnet field (Holmes and Alliance machines), were constructed to work only a single arc with commutated direct current. Such were the Gramme machines of 1876, the Wallace of the same date, and the Siemens and Brush machines of a year or so later. The arc voltage was the same or nearly the same in these, but the current, according to the size of the machine, varied widely, being in some as low as 10 amperes and in others as high as 30 or 40 or more amperes. While the current values varied somewhat as the single arc burned with varying separation of its carbon, the current at any time was stable, without surging or fluctuations, such as might have been expected from the nature of the arc resistance, which was substantially the only resistance in circuit. But there were elements of compensatory character present in the circuit. As the current in an arc increases, the section of its hot gaseous conducting flame likewise increases; the resist-

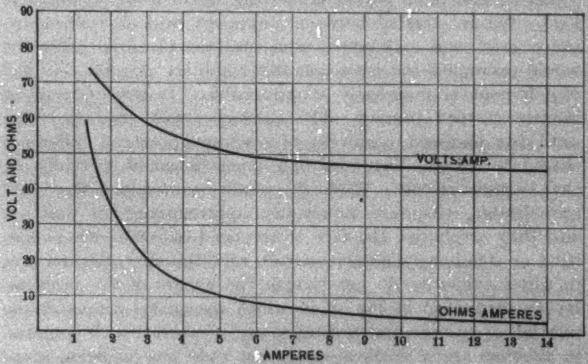


Fig.1

ance falls as more material is volatilized, and more ions are furnished to conduct the current, unless at the same time the length of the arc itself be increased to compensate therefor. Most of the early arc lamps used with these machines possessed the feature of automatically lengthening and shortening the arc following the current changes in the arc-separating lamp magnets, this tending to regulate and keep constant the current strengths. The lamps were in fact called "regulators". But while this "floating arc length", as it may be called, assisted in securing stability, it would not have been of itself sufficient in the absence of other causes. It would have been too late in its action and of insufficient range.

When we examine the conditions of the circuit in these early machines, we find a large relative resistance in the circuit with the arc. As an example, a small Gramme machine of 1877 had a total circuit resistance including its arc, of 3.66 ohms, only 1.87 ohms being in the arc; the internal and external resistances were nearly equal. A Wallace machine had a total resistance of 7.83 ohms with only 2.77 ohms in its arc. An early Brush single-arc machine had 2.95 ohms total with 1.67 ohms in the arc. This relation of resistances would of itself be ample for securing stability of current, except that the dynamos being series-field excited, were of a nature to enhance current variations in the circuit by such variations reacting at full value through the series field. The machines would on this account be more likely to have unstable current. We now know that in such cases the high armature reaction allowed, and the amount and kind of iron and its nearness to saturation, were potent factors in the stability which existed. At the time these machines were designed very little was known of these matters, and the success obtained must have been largely the result of "cut and try", the experimental method. It was certainly easy to make the mistake of using too heavy iron sections, less armature reaction, less saturated field, with the result of using much less copper and obtaining even a more efficient machine for an equal energy output, and a better design if it had to work over dead resistance, but one which with an arc for its external work or load would not attain stability in current until the value was so large as to overheat and destroy the structure in a short time. The problem was the more difficult when later it was to be designed for a series of ten or more arcs, for in that case the steadying effect of internal resistance, so potent in the case of the single-arc machines, could no longer be counted upon, such resistance falling more and more in relation to the external resistance with the size and increased capacity. In machines of a capacity of thirty to forty arc lights in series, the external resistance might bear to the internal a relation of approximately 10 to 1. There still remained the regulating effect of the lamp magnets giving a "floating arc length", and this action of the so-called regulators or lamps was the more important, as in the larger machines the time-constant of the circuit increased, giving more time in which the lamps could act to extend and shorten the arc lengths. When surging or instability took place it was marked by a lower rate of variation in the large machines than had been the case in the smaller ones, and consequently the period in which the lamps could act was more favorable. In series dynamos of large size the field-magnet reactance is naturally large, and mechanical adjustments of arc length were possible on account of the resultant sluggishness of the current variations indicating instability. There was, however, a more important property, the full significance of which was only realized at a later date.

Dr. John Hopkinson in 1879 called attention to the method of plotting curves, afterward called "characteristic curves" by Marcel Deprez. It was shown that by a study of the characteristic of a series dynamo the condition of stability or instability of current when working an arc in its circuit could be predicted. It is not necessary to repeat the work done by various investigators in the study of these curves. Suffice it to say that the conclusions as to instability are evidently modified somewhat under the conditions above pointed out, where the circuit has high reactance and there is time for the lamp mechanism to act in changing the resistance in circuit—increasing it when owing to an increase of current it tends to fall in the arc, and decreasing it when the current tends to die out, owing to the higher arc resistance which follows a diminished arc current.

At one time series direct-current circuits, made up of what were known as "short arcs" as distinguished from "long arcs", were employed in lighting to a considerable extent. In these short arcs the carbon electrodes were run so close together that there was but little appearance of any arc-stream between them. The arcs were hissing arcs, giving out continually a frying sound and frequently dropping out mushrooms of graphitic carbon which accumulated on the negative or lower carbon. The light itself was yellowish and came largely from the highly heated ends of the carbons next the slight separation or imperfect arc. In practice the current was about double that of the normal long arc; the voltage at the arc was about one-half. With the long arc the current was about 10 amperes and the voltage 45 to 50. In the short arc these amounts were approximately 20 amperes and 25 to 30 volts. Comparatively, the light production for a given energy expended was lower in the short arc. Reasonable life of carbons was only obtained by using extra hard sticks heavily copper-plated. The line losses formed a much higher proportion of the energy supplied. Unless the copper section were quadrupled in the case of the short arcs as compared with that used with the long arcs, the same loss per mile could not be attained.

This matter is, however, aside from our subject and is mentioned only as indicating one of the reasons for the non-survival of the type. So far as stability is concerned, however, since the lights were in considerable measure like dead resistances, it was far more readily obtained; it did not depend to such a large degree on the characteristic of the dynamo. So far as the writer is aware, these short arcs or semi-incandescent arcs were the only ones ever successfully run in series on shunt-excited arc dynamos, machines in which the proportioning was much more easy and more akin to that of constant-potential types. Despite the fact that a greater efficiency in the dynamo itself could be reached, the system gradually went out of use. It is readily seen that where the arcs were so short as to be only incipient arcs, the regulating effect of the series magnets of the lamp mechanism was quite important in determining the strength of current used. Slight increase or decrease in the separation of the carbons gave a larger change in the working resistance and also in the light. A similar extent of movement of electrodes toward or from each other in the long arc would have scarcely any effect. The floating arc condition was then quite essential to practical operation of these short arcs. The lamp mechanism was indeed a " regulator " in this case.

The various forms of series arc lamps involving differential lamp magnet mechanism of one or another type secure in greater or lesser degree the floating arc condition as distinguished from the " fixed separation ", a feature of some types. As exemplifying the importance of this regulating feature upon current stability, the writer may perhaps be permitted to recall an early experience in arc dynamo design. The first series arc machine designed and built under his supervision, was also the first dynamo having the three-coil (star three-phase) winding with three-segment commutator. This machine, at a speed of 750 rev. per min., ran a series of eight lamps at 10 amperes, with 45 to 50-volt arcs, and survived room temperatures of a bakery in the midsummer of 1879 in Philadelphia, the thermometer on the wall nearby showing sometimes 120° up to 140° fahr. in the early evening with the ovens in full operation. The machines had been carefully proportioned in the light of all available information which could be discovered at the time. There was very little to guide one in this task. Nevertheless, the current of the machine was stable at the current for which it was designed, although no experimental machine had preceded it. Further, there was no change needed in the windings and it remained in service for years thereafter.

Several similar machines were made after the trial of this first one. Following these there was constructed in 1880 a small compact machine for a circuit of 16 arcs in series, but the proportions were less conservatively chosen, and the armature strength was less in proportion to the field, so that regarded from a later standpoint the armature reaction was too small to give a proper droop in the characteristic at the current value of 10 amperes, for which it was designed. The iron sections were also liberal. It was found capable, when driven at 800 rev. per min., of maintaining its full quota of lamps, 16 in series, but although the lamps had the series-magnet regulating feature, the current was decidedly unstable, and only became stable at higher values, about 15 amperes, too high for the safety of the windings. It was observed, however, that if in the circuit there was introduced a single supersensitive lamp, or one in which comparatively large extensions or shortenings of arc length followed quickly upon minor current changes, an artificial stability was produced, which, in spite of the evidently unsuitable characteristic, as now regarded, allowed the lamps to be operated at their intended current of 10 amperes, or even less. The behavior of the dynamo as to heating and efficiency, etc., was then satisfactory.

On account of the relatively high duty of the machine, less weight of wire and cost, it became actually a debatable point whether the supersensitive regulating lamp might not be shut up in an iron box and maintained as a permanent part of the circuit in practice. Later work, however, developed the fact that by changing the manner of commutation, the same machine became quite stable at the current intended, but at a sacrifice of output which could only be met by running at a somewhat higher speed. Naturally the stability obtained was accompanied by a somewhat lowered efficiency, but when attained was sufficient to render the circuit independent of any adjustment of arc length by the magnets of the lamps, except that of feeding as the arcs were lengthened by consumption of carbons. The actual change in the commutation made as above referred to consisted in rearranging the brushes of each pair, positive and negative, around the commutator from what was called forward regulation position to that which became standard in the Thomson-Houston arc machines afterward built. In the forward regulation the slots in the three-segment commutator were straight and parallel to the axis, in which case a pair of connected brushes on each side separated by a definite angle was used. Sometimes a single brush at each end of the diameter of commutation was applied, and the slot between the commutator segments offset so as to cause the segments to overlap or cover considerably more than 120° each, giving like results in commutation. In the later method, and that which became standard, there were two pairs of brushes. The commutator was made with straight slots parallel to the axis, and a positive pair of brushes placed on one side, and the negative pair on the other side. The brushes of each pair were spaced apart 60°, so that virtually a segment of the commutator was in contact with the positive or negative brushes through 180° in the full-load position. In regulating for a decreased number of lamps in series, the brushes in forward regulation were moved progressively forward, while in the later method the forward brush of each pair was adjusted forward only so far as to cover the spark developed, while the rearward brush of each pair was moved backward to the position where the same value of current was given to the circuit. It was found that if in either form of regulation the current was stable at full load it never became less so on diminished load, but rather more stable. This was to be expected. It is interesting to note in passing that if the arrangement of the brushes was intermediate between that of forward regulation and that of the later standard placing referred to, the circuit was characterized by great instability, so great as to make it impracticable to use the machine at all for an arc-lamp load.

These matters were, of course, the result of experimental trials of available apparatus. The explanation is that the needed droop in the characteristic curve of the two forms or arrangements was the result of opposite or conflicting causes incompatible with each other, so that an arrangement intermediate between them was not practicable. There is no space here for a more detailed analysis, which would itself be an interesting and instructive subject. It may be noted that one of the reasons for discarding the setting of the brushes as in "forward regulation" was that the wear of the brushes tended to extend the arc of contact and virtually to increase the overlap of the segments or the arc of revolution during which a segment was in contact with a positive or negative brush. This followed as a result of the tangential position of the brushes, which were made of slit strips of hard-rolled copper, as is well known. Lack of care in trimming and adjusting the brushes would, in fact, so extend the arc of contact that instead of stability, great instability would result. This showed clearly that stability depended on a restricted arc of contact or overlap of contact between adjacent segments under the brushes. If the field were relatively strong this overlap needed to be diminished. With a weaker field and greater armature reaction the arc could be extended. In consequence of this, and for the reasons above stated, the second or later arrangement was the final one adopted.

Another and curious stumbling block so far as stability of current was concerned was met later. Several sizes of Thomson-Houston arc dynamos were designed and built at New Britain, Conn., in 1882–1883, giving perfectly stable current without dependence on the regulating action of lamps or floating arc condition. The manufacture was removed to Lynn, Mass., in the fall of 1883, with the result of importing instability of current. The same patterns and proportions were used, all elements of construction apparently being retained. A change had been made in the lamp mechanism whereby there was now no longer any dependence of arc-length on the current fluctuations, the control of arc-length and feed being obtained by a derived circuit or shunt-potential magnet only. At first it was thought that this change in the lamp mechanism was the cause of instability, and as assisting to that conclusion, experiments showed that the Lynn-built machines could operate a circuit of lamps having differential magnets (differential lamps) smoothly, and without instability. These were the old so-called D lamps; the new lamps being the old well-known M & K type.

As a remedy for the trouble, and one resorted to while the true cause was being investigated, there was established a short-circuit band of copper wire around the field cores parallel to the winding. This device at once gave stability to the current with both types of lamp. Meanwhile it had been determined that machines built in New Britain could operate with a stable current with either type of lamp in circuit, showing that they at least were independent of the floating-arc condition, or did not need the regulating effect of the lamps to insure stability. It was further found that machines built in Lynn from castings made in New Britain gave stability with either type of lamp. This led to the suspicion that in the cast iron itself lay the true cause. Analysis showed manganese in the New Britain iron and very little in the Lynn foundry iron. Special melts made in Lynn with the same mixtures of pig iron as were used in New Britain gave at once stable current and ended the difficulty without recourse to the closed copper band on the field, which demanded the sacrifice of considerable copper.

If anything will serve to show the pitfalls to which the arc-dynamo designer was subject, the above incident should suffice. The difference in the iron was evidently a difference in magnetic stability, rigidity, or hysteresis. In a dynamo machine the iron of which is magnetically stable or rigid, as when the hysteresis loop is wide, there is an absence of response to minor current fluctuations, which response is one of the causes of instability in series-wound machines. Put differently, it may be that there is an *ascending* characteristic curve, derivable from current and potential determinations while these are increasing, and a *descending* characteristic derivable from similar determinations, while these are diminished or diminishing. The greater the difference between these two the greater the stability of current, and the further down toward the origin one may work without instability. In machines with large iron projections on the armature core, such as the Brush arc machine, it is likely that there would be but little difference ascending or descending, owing to the magnetic vibration accompanying the operation of the machine; but it is conceivable that with steadily-driven, smooth-core armatures the hysteresis of the field iron would be a controlling factor. Doubtless, in the case above described, a study of the magnetic qualities of the two irons would have disclosed the difference, so important in its practical effect. But it was then too early and there was too much else to be done at that time.

In apparatus in which potential differences of thousands of volts had to be maintained with only a single slot in the commutator between the brushes at such great potential differences, it can readily be understood that flashing or arcing over a slot might short-circuit or reduce the line current so much as to introduce a different kind of instability. Such a flashing or arcing in the slot was of the nature of an alternating arc. A segment of the commutator left the brush with a small trailing spark, showing a diminishing current reaching zero at a small distance in advance of the brush. Immediately thereafter the potential of the segment was reversed and attained a high opposite value, which, as an alternating arc, would jump the zero current position, especially if any heated gas remained in the slot. The writer has been frequently credited with having adopted as a bold expedient the well-known air-blast mechanism to blow out the sparks at the commutator. Nothing could be further from the fact or more mistaken. The real function of the air blast was to ensure the non-existence of heated gas at the zero current, to replace it with cold air and prevent the possibility of the next alternation re-establishing the arc and short-circuiting the commutator over the single slot between positive and negative brushes. The action to be secured was carefully reasoned out in advance of its trial and application. Without it the instability of circuit conditions would have rendered operation entirely impracticable, owing to incessant alternating arcs between commutator segments. Although these considerations apply to apparatus which is rapidly being replaced by other means of distribution, the writer feels justified in here presenting them as matters of history not generally understood.

The arc-light dynamo devised by Charles F. Brush was the pioneer machine in series-arc work, and it is proper to inquire as to the features which made it successful so far as stability of current was concerned. It was early shown to possess a drooping external characteristic, but it is safe to say that in the earliest types there was still dependence upon the regulating feature of the lamp or floating-arc condition. The lamps were of the differential type. It is also a fact that the peculiar property conducing to stability both in the earlier and more recent designs was largely due to an almost critical proportioning of the proper extent and relative sections of the pole horns adjacent to the armature on each side. In a conversation with Mr. Brush in 1878, the writer remembers that he laid emphasis on the fact that even in the single-arc machines then before us, a comparatively slight variation in spacing or the arc covered by the pole pieces would destroy the stability of current, so that, as he said, he could do nothing with the machine. This was before the day of characteristic curves. The later Brush machines of large capacity for multicircuit work up to 125 arc lights or more, many of which have been built at Lynn, Mass., depended more than ever on the close proportioning of armature and field, and more particularly upon the form section, material, and arc covered by the pole horns. By careful adjustment an external characteristic curve having an almost vertical droop at a current value a little beyond the working current strength was obtained, rendering the current stable regardless of the regulating effect of lamps, and leaving but little to be done in regulating for variations of the number of lamps in circuit.

There is given in Fig. 2 an approximate showing of the relation of external characteristics of three Brush machines of different periods. The curves are not accurate, but merely indicate general types. Curve A shows the general form of characteristic of one of the earlier bipolar types. Curve B is that of a later type of larger capacity (125 arcs in series) built in Cleveland. Curve C gives the approximate curve of a still later machine of the same capacity built in Lynn, the two latter machines being of the four-pole type. There was a progressive saving in copper obtained. In the machine of curve A, the copper was approximately 50 lb. per kilowatt output, in the machine of curve B, about 40 lb. and in the machine of curve C, about 28 lb.

In Fig. 3 are given three characteristics taken from one of the most recent Brush machines constructed for working magnetite arc lamps at 4 amperes at a total circuit voltage of 15,000, multicircuit plan. In regulation the machine is shunted more or less and brushes adjusted automatically for variations of load. Curve A with a little over 15 per cent of the field current shunted and spark at brushes of fixed length, indicates that the normal current point is well over on the droop which at 5 amperes corresponds to short-circuit or no voltage. With curve B, or unshunted field, the normal current point lies on the horizontal part of the curve which then droops rapidly at about 4.75 amperes and would indicate a probable short-circuit current at about 5.5. Curve C shows the normal current value of 4 amperes at no voltage and indicates the condition when all lamps are shunted and the field shunted, in this case to the extent of 34 per cent of its current. Curve A shows ample stability. Curve B indicates an approach to instability, probably capable of being prevented by the regulating feature of the lamps or floating arc condition. Curve C is, of course, an indication of most perfect stability and it will be readily understood that as the load is cut off in passing from A to C the margin of stability will increase steadily.

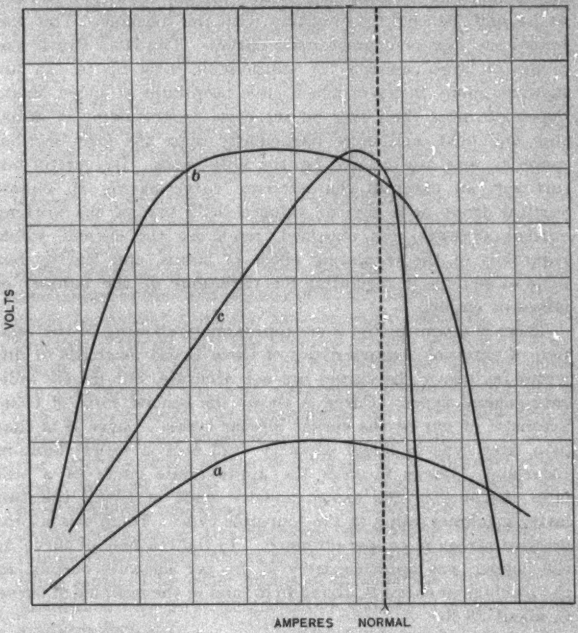
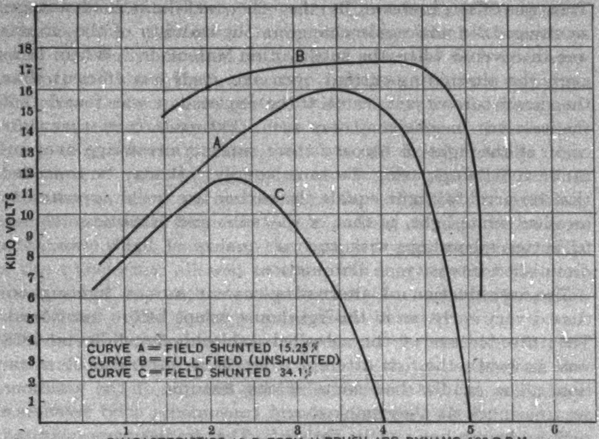


Fig. 2

It is interesting to note that in most of the early Brush machines there was applied around the field cores a closed copper band to increase the stability or prevent surging. The temporary use of this expedient in the Thomson-Houston construction has been alluded to. The closed band served to render the field magnetism less sensitive to quick changes occurring in the current of the machine, by permitting the induction of opposed currents in the band. The magnetism was thus rendered more stable and the changes in it more sluggish.

The complete theory of the various types of arc dynamos has not been worked out, and much of the designing has been of necessity of the cut-and-try order. The later work on the Brush dynamo has been ably carried out by Charles M. Green at Lynn, and the machine, on account of lending itself readily to multicircuit working, is still constructed, though the output is now relatively small. On account of the great dependence of the working and current stability upon the relations and proportions of the pole horns, it may almost be characterized as a "pole-piece" machine in contradistinction to one in which there is either an absence of pole horns or in which, if they exist, their form and disposition exert no vital influence on



CHARACTERISTICS 13 D FORM H-BRUSH ARC DYNAMO 500 R.P.M.
Fig.8

the working, particularly as concerns the stability so essential where the load consists of arcs.

It seems probable that on account of the simplicity of the wiring, the series constant-current circuit will be employed for a long period in the future for arc lighting in street service and for large spaces. The advances recently made in high-efficiency luminous flame arcs will doubtless be a potent factor in future development.

When the enclosed carbon arcs were substituted for open arcs on direct-current circuits, it was recognized that a sacrifice of efficiency of light production with a given energy was involved. This was offset, however, by the other well-known advantages accruing. No noticeable change in the stability of the circuits was discovered when the substitution was made. When, however, the alternating-current open arc, itself less efficient than the direct-current arc, came to be enclosed it was found that the sacrifice in efficiency was such that aside from the white color of the light of the arc there was no advantage over incandescent lamps using the same energy. It may be conceded that no artificial light equals the carbon arc in its approach to an ideal white light, or that of the sun; and doubtless we see to better advantage with such a quality of light even at a diminished intensity of illumination.

The introduction of alternating-current arcs in lighting occurred very early, as in the lighthouse lamps before mentioned. The introduction of the so-called Jablochhoff candle in 1878 was, however, the first attempt to apply it in general illumination. The candles had some of the features of the luminous arc, inasmuch as they smoked and consumed a solid substance such as kaolin besides the carbon. The candles were operated several in a series. Little is known of the stability conditions in such circuits, but in Paris in 1878 the alternating dynamo current was not carried directly to the lamps, but the lamp circuits were operated through huge condensers in such manner that several series of lamps were fed from the single current of larger value split up through the condensers. It is possible that this use of condensers in the distribution served to limit the current values and secure stability. Later attempts to apply open arcs of the alternating type on series circuits from constant-current transformers, met with little encouragement. Not until the success of the enclosed arc on direct current had been fully demonstrated was there any considerable opportunity to make use of series alternating-current arcs. The enclosed alternating arc operated from constant-current regulating transformers gave the opportunity. The system permitted the employment in the station of generators of large capacity with constant-potential mains, to which the primaries of the transformers could be connected at conveniently located sub-stations, while the secondary arc circuits became independent, so that leaks or grounds on one did not affect the other. This was a manifest advantage.

Fortunately no difficulty arose in securing stability of current values in constant-current transformer distribution. The reactance, or more properly the general impedance of the system including the alternating lamp magnets, which themselves assist materially, resulted in a fall of potential with increased current, and the reverse, at a rate sufficient to insure stability. The characteristic curve plotted with current as abscissas and volts as ordinates would in the constant-current transformer droop as in the arc machine, but it would droop steadily from zero current outward. In other words, the potential is at a maximum with zero current, while in the series field arc machine, except for residual magnetism, zero current corresponds to zero potential. Were, however, the primary and secondary coils of the transformer allowed to come too near together the condition would approach too closely that of a constant-potential transformer. The leakage magnetism between primary and secondary coils, when as close together as permissible, will give rise to considerable reactance values, which, as the load on the secondary is cut off, will gradually increase as the secondary is repelled to a greater and greater distance. It is necessary that the movement of the coil be effectually damped, by dash-pots or the like, or an instability due to overrunning akin to hunting will take place during changes of load. The direct-current arc dynamo with its heavy series-field coils is likely to have so much self-induction as to tend to steady the current values so far as very rapid fluctuations are concerned. When, however, the field, as in the Brush machine, is shunted more or less for regulation, this influence of the field inductance is neutralized, at least to a large extent. With the alternating-current circuit there is, of course, an entire absence of such influence upon stability; but in this case the resistance and self-induction in the whole circuit traversed by the current is sufficient for securing stable values of current. These conditions giving rise to stability naturally involve a lessened power-factor in the system, and, as is well known, the distortion of the current wave in an alternating arc, while not in the nature of a true lag, reduces the power-factor. It is probable also that the tendency to instability in an alternating-current arc is not so great as in the direct-current arc, for the arc undergoes extinguishment at the zero and does not relight until after the potential difference between the electrodes has reached a considerable fraction of the maximum.

In the more recent work with magnetite arcs and with lamps having electrodes which, for satisfactory operation, demand the employment of direct current, there was at one time a tendency to return to the use of motor-driven arc dynamos giving small current values and high potentials. The development of the mercury-arc rectifier with its apparent special adaptability to the rectification of small currents at high voltage has naturally led to its employment in conjunction with the constant-current transformer for securing direct currents suitable for series-arc circuits. The practical results so far obtained with oil-immersed mercury rectifiers have been so generally satisfactory as to indicate an extended future application. The new factor which has thus been introduced into constant-current working may of course be the cause of disturbances and instability under certain conditions, such as too high or too low a temperature in the rectifier, change of vacuum, or momentary flashing from anode to anode, indicating failure to rectify. Any cause which disturbs the circuit voltage is productive of results which may be classed as instability.

Oil-bath immersion has given control of the working temperature of the rectifiers. If too low, the condition imports instability. If too high, there is danger of breakdown. Fortunately it appears that normal working demands such moderate temperatures as are easily maintained in the oil bath. Alteration of vacuum by leakage, or by gradual giving out of gas may result in the accumulation of a body of insulating gas around the anode, interfering with the normal ionized mercury-vapor stream which conducts the current. This may cause a fading out of the rectified current, in turn causing the lamp to lower or drop the electrodes together, and thus again allow increase of current, which again separates them, and so on; a condition of surging or oscillation somewhat akin to the instability of an arc circuit when working too close to the critical point on the characteristic. Lowered vacuum also endangers the rectifier by causing excessive stresses near the anodes, which may puncture the glass. Suitably spaced shunting gaps may be provided around the rectifier as a safeguard against excessive stresses. The temperature of the rectifier tube can also be maintained by circulation of air by a fan where oil is not used. The plant includes, besides the rectifier and constant-current transformer, additional alternating-current reactance, and a direct-current reactance in the rectified current circuit, the proportions of which are chosen to insure as far as possible steadiness in the working.

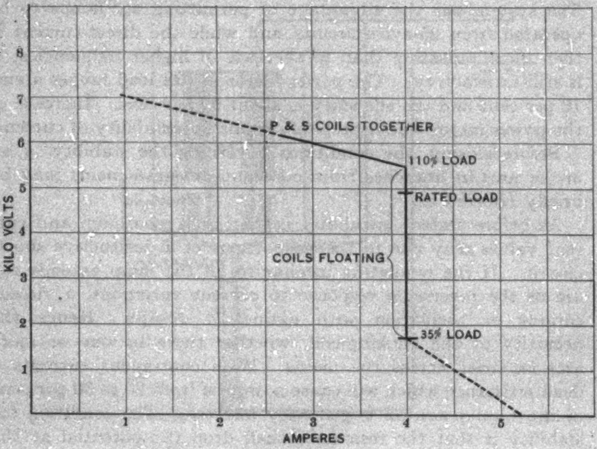


FIG. 4

If a characteristic be plotted it takes the form given in Fig. 4, which is properly the regulation curve. The vertical line at 4 amperes shows the range of constant current between 110 per cent load and 35 per cent of full load in kilovolts, the latter point corresponding to the greatest separation of primary and secondary coils as provided for in the construction of the transformer tested. Even at short-circuit the current will then not exceed 5.25 amperes. As a rule the circuit is adapted to the operation of lamps in which the arc length is either "floating" or fixed, without involving instability of current. Hence the lamps may be constructed to lift the upper electrodes and separate them to a definite distance and to drop them together at feeding, which in the case of long-burning electrodes would occur very infrequently. This manner of operating was known in the early days as " drop-and-lift " feeding, and was probably first used on any scale in the obsolete Wallace plate lamp. As before shown, such operation requires a current which is inherently stable, as no adjustment occurs in the lamp itself. As indicating the endurance of the mercury-arc rectifier itself, it may be incidentally mentioned that some of these in service have attained upwards of 5000 hours' life and are still operating. The system has the advantage of permitting arc lamps to be operated from 25-cycle circuits, and while the direct-current is then more pulsating than in the case of higher frequencies, it is still satisfactory. The power-factor at full load ranges about 70 per cent and the efficiency is about 90 per cent. Increase of the power-factor would probably result in instability of current.

Before closing, the conditions governing the stability of an arc or arcs in branches from constant-potential mains may be briefly referred to.

As before stated, instability is then at a maximum and current values may rise to the proportions of a destructive short-circuit. If the regulating mechanism of the lamp extends the arc or the reverse in response to current variations, a violent surging or oscillation with extinction results. Hence the necessity of the choking-coil, whether there be one or more arcs in series across the mains. With continuous currents a dead resistance which will cause a drop of from 20 to 30 per cent of the total potential is generally inserted. The condition for stability is that the resistance shall drop the potential at the arc with increase of current at a greater rate than that caused by increase of current in the arc itself, and *vice versa*, as is well known. This involves a serious loss of energy and many efforts have been made to reduce or minimize it. It is customary to allow the floating arc to exist and in such a case the dead resistance may be cut down, if in the arc branch a large self-induction be inserted, a reactive coil which introduces a time-lag in the current variations, allowing the regulating action of the lamp magnets to come into play. Better yet, if the lifting magnet be made a shunt of many turns around the more coarsely wound reactance or reactive coil (as invented by Higham) a supersensitiveness in the lamp mechanism is obtained which causes it to anticipate current changes or at least compensate therefor in increasing and diminishing the arc length and so preventing the fluctuations attaining any considerable value. Still more effective is the arrangement in which, as in Fig. 5, the arc-adjusting coil *C* in shunt to the reactive coil *R* is made to move in the field of the latter used as a field magnet *M*. These arrangements permit a direct-current arc to be operated between constant-potential mains with a minimum of dead resistance in series with it. Unfortunately, the saving with the carbon arc is of little practical value where a single

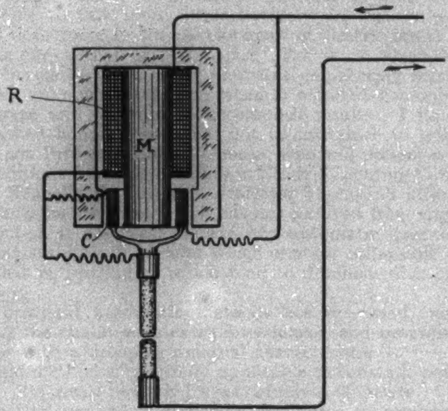


FIG. 5

enclosed arc is put in a branch across 110-volt mains. While the voltage at the arc may be thus increased from 80 volts to 100 or thereabouts, the gain in light does not correspond to the increased arc energy, on account of the comparatively low luminosity of the arc flame itself. It is possible that where the arc flame is the source of light, as in luminous arcs, the expedient may give practically valuable results, though that remains to be seen. In the case of the alternating arc across lines at constant potential, stability is readily obtained by the introduction of an impedance, or reactive coil, which need not involve any considerable loss of energy, but of course its effect is to diminish the power-factor of the system, to which also the distortion of wave in the alternating arc itself may add. Both the Nernst glower and the mercury-arc lamp share with the ordinary arcs the disability of invoking instability of current unless special means are provided to prevent it. No special consideration needs therefore to be given to them in this general review of the subject.

DISCUSSION ON "CONDITIONS AFFECTING STABILITY IN ELECTRIC LIGHTING CIRCUITS." NEW YORK, JANUARY 8, 1909

Elihu Thomson: The paper I have to present is in large measure incomplete. It is merely a sketch or outline, and much of it is historical, going back to the early days of the inception of the art which this Institute represents. It was thought it would be well to bring together in one paper and place upon the records of the Institute some of the historical facts connected with the subject treated of in the paper.

President Ferguson: The Institute is especially fortunate in having been able to induce so distinguished a member as Professor Elihu Thomson to present this paper to you this evening. There is probably no man in this country who is able to talk more authoritatively on this subject, or who has done more in the development of electric street lighting, than the author of this paper. The work which he did was in the early days, when electrical engineering was comparatively unknown, at a time when it required not only skill but courage and patience to accomplish results. I have the distinguished honor, gentlemen, not to introduce to you, but to call upon Professor Elihu Thomson, who will present a paper on "Conditions Affecting Stability in Electric Lighting Circuits."

A. E. Kennelly (by letter): Professor Thomson's interesting paper discusses a subject which has not received from engineers the attention it deserves; namely, the automatic maintenance of current stability in circuits which contain collapsible resistances; that is, resistances which tend to diminish with current flow.

Two principal automatic methods are discussed: namely, ballasting the circuit with extra impedances, and providing the generator with a drooping external characteristic.

The first method is especially applicable to constant-potential circuits. Its weak point is its wastefulness of power.

The second method is especially applicable to constant-current circuits.

The arithmetical relations that determine the restoration of stability to such a circuit are simple enough, if we regard the matter merely from the standpoint of static equilibrium; but in practice the problem is complicated by kinetic actions, such as the time-interval of arc-mechanism response, the time-interval of engine-governor response, the time-interval of field-magnet response, and other time-intervals alluded to in the paper. Consequently, the complete practical problem, as presented in a series-arc circuit, is arithmetically very complex, even with the accumulated experience of 30 years. It must have appeared yet more intricate in the early years of arc lighting.

It is very interesting to learn that a supersensitive arc-lamp mechanism in the series-arc circuit was found sufficiently effective as a stability regulator to make its practical adoption, in the early days, worthy of consideration.

The remarkable degree of current-stability in series-arc circuits supplied through constant-current or tub-transformers, which is familiar to all who have operated such circuits, is clearly explained in the paper. The external electromotive force characteristic shown in Fig. 4 would fall much too precipitately for effective use in a generator, as may be seen by comparing it with curve *B* in Fig. 3. The current stability in the case of the tub-transformer is only rendered possible, with the vertical drop of voltage characteristic in Fig. 4, by the automatic balancing of gravitational force against electromagnetic repulsion in the manner well known.

It is a curious fact that the property of diminution in resistance with current which may bring about current instability in an arc circuit, is the property which is utilized in wireless telephony to throw a vertical conductor into sustained electric oscillation, by means of voltaic arcs shunted by condensers.

Alex Dow (by letter): It is well known that any cause which disturbs the circuit voltage is productive of results which may be classed as instability and, conversely, that circuit conditions of apparently minor importance may be effective in maintaining stability. For instance, a constant-current Brush machine on a Mississippi River steamer was used to operate two 20-ampere, 50-volt arcs in series during the loading and unloading of the steamer, and, when the steamer was under way, to operate a 40-ampere, 50-volt searchlight. The field windings of the machine operated in straight series on the former service, and in multiple-series on the latter service, so that the field ampere-turns were constant and the armature ampere-turns were double when the searchlight was operated. The latter condition should have tended to produce stability. Nevertheless the two arcs in series were beautifully steady, while the single searchlight behaved sinfully. The completely successful remedy applied was the insertion of inductance in the searchlight circuit, in the form of some large iron wire wrapped over asbestos paper on a gas-pipe core, in which gas-pipe core sundry pieces of old iron found on the steamer were inserted to make the final adjustment.

Another instance. Two new circuits of *M* and *K* lamps in which the arc-length was controlled by a shunt round the arc, were unsteady when operated from their proper Thomson-Houston spherical armature machines. They were entirely steady when operated from Brush machines, and the Brush differential lamps were entirely steady when operated from the Thomson-Houston machines. Consequently, this exchange was adopted as the regular rule of operation. Subsequently it was found that if one-quarter to one-third of the lamps on the circuit were of the Brush differential type, the circuit would be steady on either machine.

In my experience the worst case of circuit instability was that of several circuits each intended to carry 150 arcs. They behaved very badly, and it was necessary to adopt a quick and a cheap remedy. The generators had not the drooping characteristic. Their short-circuit current was about twice the normal current. But they had an exceedingly effective regulator which would control closely the current supplied to a circuit naturally stable. The constructing engineer had combined those machines with shunt-wound arc lamps, not the lamps usually operated in conjunction with the generators. Each string of 150 lamps was served by rubber-insulated, lead-covered underground cables of high insulation resistance, high static capacity, and inadequate resistance to puncture. The capstone, so to speak, of the combination was that the lead cover of each length of cable was intentionally kept out of contact or connection with the lead covering of the succeeding lengths and was, because of frozen soil, virtually insulated from earth.

When these 150-lamp circuits were operating, all the telephones on the west side of that large city went out of business. One hundred modern wireless installations could not have been more effective in disturbing the ether. But the circuits would not stay in operation. The machines spilled, the cables punctured, and the arc-lamp posts burned out. The remedies applied were, first, the earthing of each section of lead sheath; second, a rearrangement of the circuits so that some old differential lamps were included in each string of shunt-wound lamps; third, the steadying of the machines by various devices known in the art; and finally the substituting of different machines with marked drooping characteristics for the original efficient but very sensitive generators. The last remedy was, of course, final, but the effect of the connection of a comparatively few differential lamps was surprising.

E. W. Rice, Jr.: This subject is of great interest to me, because I had the rare privilege of association with Professor Thomson in the early days of which he speaks. I still have vivid recollections of the difficulties surrounding the design and manufacture of electric generators that would satisfactorily operate a load of the inherent instability possessed by the electric arc. It is easy for us with our present-day knowledge to discover the cause of those early difficulties. I doubt if the younger generation of electrical engineers can form a proper mental picture of the conditions surrounding the work of the pioneers in electric arc lighting. In those days practically no electrical measuring instruments were to be had; it was years before the ammeter, voltmeter, and wattmeter were invented. Besides this, the confidence of financiers in electrical inventions was not particularly great, and cash was notably scarce.

Without seeming to depreciate to the slightest extent the achievements of other workers of that period, I believe I am merely stating a historical fact in saying that the author of this paper had, of all his contemporaries, the clearest view and the strongest mental grasp of the electrical problems then pressing for solution. For some reason, probably because of his characteristic modesty, Professor Thomson has failed to call attention to the fact that the first scientific investigation of the properties of the electric arc was made by him with, I believe, the assistance of Professor Houston some time in 1878 or 1879, and that a paper setting forth the result of the investigation was published in the *Journal of the Franklin Institute* at the time. This paper clearly sets forth, among other interesting facts, the laws governing the variation of the resistance of the electric arc as an inverse function of the current, from which the inherent instability naturally follows.

I am also able to say that as far back as 1880, when I first became professionally associated with Professor Thomson, he frequently explained to me, in much the same language as that employed in the paper he has just read, the characteristics necessary for a dynamo successfully to operate a circuit of arc lamps. However, for the reasons he has explained, it was not always possible to realize these views in practice. I remember we often wished that an arc lamp would behave like a respectable dead resistance.

It is interesting to note that the early machines operating but a single arc lamp undoubtedly owed a large portion of their success to the high internal resistance, which improved the stability factor, and that the problem, as usual, became more serious when an attempt was made to improve the efficiency. Unfortunately, it seems to be a general law of nature that the highest efficiency is likely to be associated with the greatest instability. However, it is worth while to try for efficiency, as in the long run the most efficient system, if practicable, will survive, as instanced in the relatively short vogue of the inefficient so-called "short-arc" system described in the paper.

Referring again to the earlier one-lamp machines which were operated at widely different currents, I think this variation was probably partly due to the fact that stability was not always found at the designed current, and machines, being small and of relatively large radiating surface, could be operated at that current which gave stability without serious overheating. Professor Thomson's description of the early machine which operated satisfactorily only when artificial stability was produced by means of a single supersensitive arc lamp, and his suggestion that it might be desirable in practice to place such a lamp shut up in an iron box as a permanent part of the circuit, recalls to my mind that at a considerably later date I actually made use of this early experiment. My application of this device was made at a time when I was placed in charge of an exhibition of arc lamps which was made by the Thomson-Houston company in Boston some time in the year 1882. For some reason the particular machine was unstable. After trying various expedients, I concluded that our exhibition was doomed to failure unless some immediate remedy were applied. As it was impossible to make any general changes in the machine or arc lamps, I arranged one of the lamps as a supersensitive stability regulator, and kept it operating in a part of the space where it would be unobserved by the public. The remaining lamps were, as I remember, entirely satisfactory. After the exhibition the machine was properly tinkered until it worked in a satisfactory manner.

Professor Thomson mentions one method of improving the stability, or even creating stability, in a machine of unstable characteristics, which consisted in establishing a "short-circuit band of copper wire around the field cores parallel to the winding." I remember this device as a sort of powerful medicine that could be used successfully only in small doses. It, of course, had the objection mentioned by Professor Thomson, of increasing the amount of required copper, but I remember it also had the added objection that if the short-circuit band were made of too large cross-section, so as to become a fairly good secondary circuit, the machine had the characteristics of a separately-excited machine. Under such conditions any flashing of the commutator was enormously increased in intensity and prolonged in time. So great was this fault that for this reason alone the machine would become uncommercial. On one occasion one of these machines gave so much trouble that I was sent to investigate its cause. I found the machine, of 10-lamp capacity, entirely stable and satisfactory so long as flashing was prevented; but if for any cause a flash occurred at the commutator, the flash would continue for so long a time as actually to extinguish the arcs, seriously interrupt the service, and exhaust the patience of the mill owner. The machine had to be replaced. After the short-circuit band was reduced to proper proportions, the same machine was found to operate in an entirely satisfactory manner.

It is pleasing to note the valuable and timely suggestions made in the closing paragraphs of the paper, which point out the possibility of increasing the efficiency of the already extremely efficient flaming arc lamp, by employing methods to maintain stability with minimum loss.

Dugald C. Jackson: When I was at Cornell University the laboratories possessed one of the old Wallace arc lamps with plate electrodes made of gas-house carbon. The arc formed between adjacent edges of these plates was prodigious, and absorbed a corresponding volume of current. It wandered from right to left and from left to right at will, along electrode edges perhaps a foot long. It was sometimes here and sometimes there, at its own volition, and the illumination afforded was too erratic to be useful.

Arc lighting with cylindrical carbons $\frac{5}{8}$-in. or less in diameter had even then come to stay; but there was a contest on between the short or hissing arc of approximately 20 amperes and perhaps 35 volts, and the long or silent arc of approximately 10 amperes and perhaps 50 volts. Each had its ardent supporters. But the hissing, flickering short arc returned so much less light per unit of energy supplied to it that its commercial life was doomed, notwithstanding the good workmanship, for that day, in the Weston shunt-wound dynamos, and the gems of mechanicians' skill comprised in the Weston lamps, which among some others, supported the short-arc or low-potential arc lighting system.

It required a bold and original man to stake out a feasible path into the domain of the unstable long or high-potential arc. But the talents of Mr. Brush and Professor Thomson, each in his own way, brought the desirable end. Mr. Brush's dynamo, judged by the dogmatic theory of that day, was viewed as a curiosity; Professor Thomson's dynamo was looked upon as a monstrosity and contrary to the proper theories of dynamo electric machines. But both dynamos abundantly proved their right to exist, and both proved the lack of imagination of their critics. The fault of the critics lay in trying to apply an incomplete theory of dynamo electric machines to one element (the dynamo) of a complete system comprising several elements, all of which react on each other in a complex manner.

In viewing the magnetic flux entering the armature of a direct-current constant-potential machine, we think of the aggregate flux as a determining feature of construction and operation. In the case of alternating-current machines, we generalize further and recognize that the position of the flux with respect to polar faces and arrangement of the armature conductors affects the form of the pressure wave and the output and functioning of the machine. A like condition seems to be even more marked in the case of the Brush arc-light machine, and *the positioning of the flux* which enters the armature core may be of an importance comparable to the importance of the aggregate strength of field. For example, in some Brush machines, I have understood that changing the polar tips from soft steel to cast iron has actually increased the capacity of the machines. These are machines in which, of course, armature coils are changed from series to parallel relations, and the reverse, by the action of the commutator in each revolution of the armature. A rational theory includes such effects; and its guiding finger points to such improvements as the reduction of copper required per kilowatt of capacity referred to in the paper, By "positioning" of the flux, I mean the distribution as it enters the armature core, say at full load, and the variation of the distribution with changing current.

My first intimate acquaintance with the Thomson-Houston arc-light machine was made with a 30-lamp machine in the later 80's in the middle of the Mississippi valley at a place where repair parts were unknown. A sleepy attendant allowed the lubrication of the blower to become defective, the runner stuck in the case, and the blower case was torn from its bolts and entangled with a mess of wreckage of the links and levers of the regulator mechanism. The accident was no fault of the machine itself. To show the essential simplicity of the type, I will say that new bolts and some links and levers roughly shaped from iron rods by the aid of a country blacksmith's forge put the machine in satisfactory and prompt commission, and it was continuously used while new parts of orthodox construction were being obtained from the factory in the East.

My observation of that machine, and many others of the same or of larger size, has led me to view the function of the blower a little differently from the manner stated in the paper. I differ with Professor Thomson, but the difference may, after all, be only a matter of definition. A close observation of the working of a Thomson-Houston arc machine shows an obvious blowing out of the arc. The blowing out is not like that of a candle, where the flame is blown from the wick by a blast; but the air blast crosses the path of an arc existing between commutator segments, stretches it to the point of rupture, and replaces the heated gases by air which is cool and unpolarized (Professor Thomson prefers the word un-ionized) and therefore will not support a renewal of the arc until it is re-established by the action of the brushes. A similar effect may be produced by blowing a brisk blast across the arc of an arc lamp.

The constant-current transformer, associated with alternating-current lamps, referred to in the paper, brought arc lighting within the scope of economical central station practice, since it made the operation of arc lighting from current generated by great generating units an assured fact. The addition of the mercury-arc rectifier has done much to extend this improvement, but it is apparent that the end is not yet. Indeed, improvement must be vigorously prosecuted if electric arc lighting is to maintain a satisfactory margin of supremacy over the new gas-burners for outdoor lighting.

C. M. Green: The early observation of armature reaction is, in my opinion, the basis of all of our arc machines of to-day. Under full-load conditions the point of commutation is under the following pole piece, and as the load is decreased, or lamps are cut off, the point of commutation goes still farther under the following pole piece. The regulation of various machines is accomplished in various ways. In the Thomson-Houston and Fort Wayne machines the final adjustment or regulation is accomplished by means of varying the armature reactions—by overlapping the double brushes in the Thomson-Houston machine; by short-circuiting the armature during part of the revolution and separating the double brushes in the Fort Wayne machine. In other words, in the Fort Wayne machine with constant current through the field there are less active conductors in the armature under full load than under no load. The regulation in the Brush, Schuyler, and Excelsior machines was accomplished by varying the field strength—in the Brush and Schuyler machines by shunting more or less current through a rheostat and in the Excelsior machine by varying the number of turns on the field.

The short-circuit bands around the fields common to both the Thomson-Houston and early Brush machines undoubtedly had a very beneficial effect. We have found other ways of obtaining stable operation as may be seen from the following:

Brush arc generators			
No. of machine or class	7.5	12	13
Volts rating	2500	8500	15000
Amperes	9.6	6.6	4
No. of commutator	3	4	4
Volts per commtuator section	833	2125	3750
Temperature rise of pole shoe above air for	270° cent	11° cent	30° cent
Material of pole shoe	Cast iron	Laminated	Cast iron
Closed copper band on fields	Yes	No	No
Pounds of copper per kw. output	53.7	29.5	26.2
Efficiency full load	70.5	88.0	85.4

For stability of operation of machines on an arc-lamp load, one of the most essential features is the saturation of the iron. An examination of Fig. 3, curve *C*, shows that there is very little saturation until the curve drops very abruptly. At this point the armature bobbins are commutating under the following pole tip, and the pole shoe becomes very highly saturated just beyond the magnet core. Into some 0.5 in. holes bored in some of the shoes I inserted a thin steel rule; the rule was attracted very strongly to the iron, showing a heavy magnetic field across the hole. The magnetism held the rule so tightly that it could be twisted about 30° in 3-in. lengths. I doubt if there are any machines manufactured to-day in which the saturation of the iron is higher than in the Brush machine.

I desire to add another characteristic curve to the two which are given in Professor Thomson's paper, Fig. 2 and Fig. 3; one showing the effect or characteristic of varying the length of spark on the commutator, entitled "External Characteristic No. 11 Brush Arc Generator." When the generator is running on short-circuit, if the spark length be increased, the current rises; this however, continues to a less and less degree, as the full arc-lamp load of the machine is approached. At the point of about maximum output a variation in the length of spark has very little if any effect upon the current output of the machine. If the machine is still further loaded, the brushes move backward, and if the spark is lengthened out the current falls off rapidly; in other words, a short distance beyond the point at which changing the length of spark does not affect the output of the generator, is the maximum load of arc lamps which the machine will carry. In addition to this, it is the maximum output which can be obtained from the machine. Either short-circuits or open-circuits will decrease the load and the power required to drive the machine. Generally speaking, arc machines do not operate well at reduced current, and the kilowatt capacity is practically in proportion to the square of the current, and the operation is poor, due to the fact that the iron is not saturated at lower current.

The first 120-lamp 6.6-ampere Brush arc generator was developed in Lynn, worked satisfactorily, and was sold to the Boston Electric Light Co. Shortly after that they installed 18 more machines. When about one-half of them were delivered I was told that they were unsatisfactory. The difficulty in the machines was corrected after extensive tests by changing the material in the pole shoes from steel casting to cast iron, taking 360 lb. of copper from the fields, rewinding the rheostats, and increasing the rating from 8000 to 8500 volts.

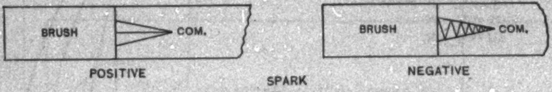


FIG. 1

Later additional changes were made, reducing the amount of copper in the original machine by 636 lb. or more than 25 per cent.

Experiments were conducted at Cleveland and approximately 500 lb. of copper were taken from the fields and the magnet cores were increased from 5.25 in. to 6 in. in diameter. The generator operated satisfactorily on a resistance load, but when the machines were operated on an arc-lamp load they were not satisfactory. They would run satisfactorily to about 5000 volts, but not to 6250 volts, their rated load. Characteristic curves were taken up to about 5000 volts and were satisfactory for the operation of arc lamps, but when the field strength was increased to obtain a higher voltage the peak of the characteristic curve went out to 12 or 13 amperes. Arc lamps could be operated at this current, but it was not what the customer wanted. About two years later further experiments were carried on, and we succeeded in reducing the copper on the fields 636 lb. and the machines worked satisfactorily.

I thought we could reduce the magnetic leakage in the machine and increase the output by removing the sharp corner from the back ends of the pole shoes by making the radius of the curve about 0.25 in., but the output was reduced 5 per cent or 300 volts. I also conducted further experiments, displacing the pole shoes somewhat, about 2 in., from the center of the magnet cores. I found on these machines that a change in the direction of rotation would give an output of four to one, depending upon whether the long end of the pole shoe was leading or trailing. With the long end in leading position, the machine gave the larger or maximum output. The commutation, however, was not satisfactory over the necessary range. Another peculiar thing in arc generators is that the brushes move backward with increasing load, which is apparently the reverse of constant-potential machines; but in both machines the brushes move forward when the resistance in the load circuit is reduced.

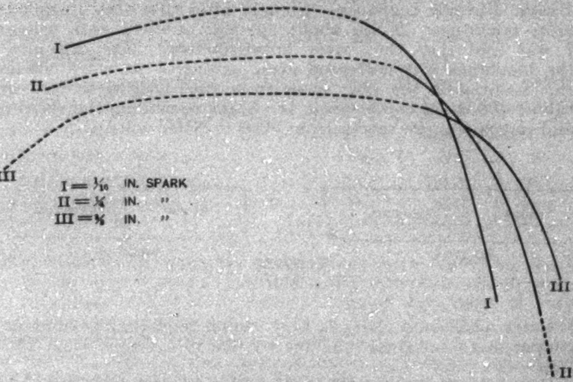


FIG. 2

The Brush and also the Thomson-Houston arc generators possess the peculiar property of allowing us to change the direction of rotation of the armature, keeping the direction of the current through the field the same and maintaining the same relative position for the positive and negative brushes on the commutator. This seems wrong, but theoretically it is right. The instantaneous fluctuations in current of the Brush arc generators amount to about half a per cent. I do not know exactly what it is with the Thomson-Houston machine, but I know it is many times greater. The steadying effect and alternating voltage across the fields of the Brush machine are negligible. In the Thomson-Houston machine the steadying effect I believe to be very appreciable and essential, and if my recollection is right, the alternating voltage across the field amounts to about 75 per cent of the rated direct voltage. This varies somewhat under different conditions of load.

I think the Brush multicircuit arc machine has interfered more with telephone service and done more to improve it than any other machine, by forcing the telephone companies to put in metallic circuits. We have also experienced trouble in operating these machines on underground cables. I should like to bring to the notice of the Institute the use of a transformer on a fluctuating direct Brush circuit for the purpose of preventing surges between the generator and the circuits, which tend to puncture the insulation on the cables but as yet have had no effect, so far as I have been able to find out, on the generator. This seems strange when a rated 8500-volt machine usually breaks down on about 10,000 volts, alternating current, jumping from the armature bobbins to the pole pieces.

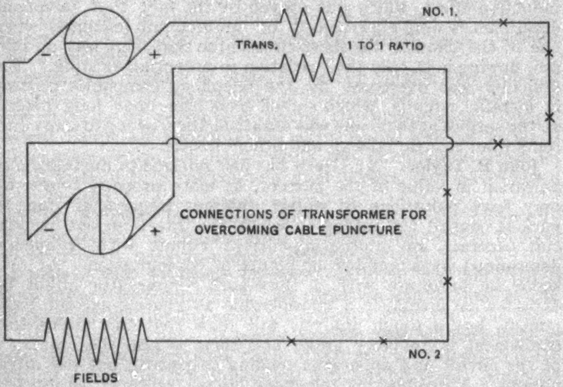


Fig. 3

The transformer is so connected that the currents through the windings neutralize each other. If we put capacity in the circuits, with the varying voltage which is generated between different commutator sections, we will have an extra current flowing through the transformer due to the capacity, and this will transfer part of the high electromotive force from one loop or section of the generator circuit over to the other so that there will be very little alternating voltage between the negative brush in the figure and that end of the transformer winding connected to load in series. On the 12 Brush arc generator rated at 8500 volts, 6.6 amperes, two-circuit machine, the alternating voltage across the transformer is about 800 at full load. The larger the amount of capacity or length of underground cables in the circuit, the greater the alternating voltage across the transformer, so that we will have changed from an unstable to a stable condition by the use of the transformer, and the electrical surges in the circuit which punctured the cables are cut out, but they had no effect so far as we could observe upon the machines or upon the lamps.

The disturbances on the telephone lines, either grounded or common metallic return, were due to the electrostatic effect, or to the wave of voltage which continually traveled along the lighting circuit. They were not due to the current or magnetic inductive effect, which was proved by the fact that telephone disturbances were experienced on multicircuit machines when one of the circuits was short-circuited so that there was no current flowing in it, only the variation in potential existing. The difficulty was overcome by the telephone companies putting in metallic circuits, which should have been done long before, as the service at that time was unsatisfactory, owing to stray currents from electric railway and other circuits.

John B. Taylor: Mr. Green has just referred to fluctuation or pulsation in value of the current, or more properly (since we may have pulsations of widely different frequencies due to various causes) the extent to which the direct-current arc circuit becomes an alternating-current circuit with frequency determined by a number of points of commutation. At first sight, an armature with a three-part commutator might be expected to introduce a considerable alternating-current component, but a rough analysis will show that this alternating component is not very great, and there is also the reactance of the circuit and apparatus tending to smooth out the alternations. A neighboring telephone circuit, however, as already pointed out, gives evidence of the alternating feature, and in addition I was surprised to find a perceptible alternation in illumination.

This I noticed about eight years ago while making some stroboscopic tests on alternating-current motors by the aid of a striped cardboard disc rotating, and illuminated by an alternating-current arc. About the same time some old Thomson-Houston direct-current open arcs were being replaced by 60-cycle enclosed arcs supplied from constant-current transformers; during the process of changing, both systems were in operation at the same time. I rotated the disc on one street corner near a 60-cycle arc for the edification of a friend, and on the next corner advised that no such stroboscopic effect would be apparent on account of the direct-current arc. I was surprised, however, to find that there was a decided alternation in intensity of illumination as evidenced by the disc appearing stationary at the proper speed, although, of course, the contrast between light and dark stripes was not so definitely marked as with the 60-cycle lamp.

I wish to ask if tests have been made which can be quoted to show how much alternating effect there is in the Thomson-Houston circuit with the machine under average load, and if these alternations are sufficient appreciably to affect figures for efficiency for such machines where the output has been measured by voltmeter and ammeter of the D'Arsonval or Weston type. Such meters give the mean value of current and voltage rather than the root mean square value, and in the extreme case of a rectified sine wave, ammeter and voltmeter individually indicate but approximately 0.9 of the proper value, while output in watts, as determined by their product, would show a little more than 0.8 of the true value. If this has not been taken into account, some values of efficiency on such generators might properly be increased by a small value, possibly 1 or 2 per cent.

There is one feature of stability rather outside the scope of this paper; that is, the stability of illumination as distinguished from stability of current producing the illumination. Incandescent lamps are probably the most stable form of artificial illumination which we have, while the illumination from an arc, in spite of cored-carbon and such devices, still leaves much to be desired.

As Dr. Kennelly has pointed out in his letter, the inherently unstable feature of the arc itself is now being turned to good use in wireless telegraph and telephone service.

I believe that Professor Thomson, as usual, has anticipated many other experimenters in this direction and I hope he can tell us something of his early experiments with the "singing" or high-frequency arc. It seems possible that we may have in some of the underground cable distribution systems for arc lighting a condition not unlike that which is purposely arranged for the singing or oscillating arc; that is, a capacity (made up of cable) around the arc in series with more or less reactance (principally in the lamp mechanism). If both reactance and capacity should chance to have the proper values, and the resistance and other losses were not too great, this combination might build up sufficient voltage to account for some unexplained cases of breakdown on such systems.

H. G. Stott: I would call attention to a very important historical note in the paper, where reference is made to one of the first series arc dynamos. It is as follows:

> The first series arc machine designed and built under his supervision was also the first dynamo having the three-coil (star three phase) winding with three-segment commutator.

I believe Professor Thomson can enlighten us very considerably on the point, which was recognized by him and his associates, that this was a three-phase machine, and that power could be transmitted from it and supplied to another machine by putting on what were then called slip-rings. I think from an historical point of view, it would be interesting for Professor Thomson to bring this out when he closes the discussion.

Elihu Thomson: Reference has been made to the use of a partial load of differential lamps. I remember that this was resorted to as a steadying influence in times when unstable circuits were found. It was also noticed that with an increase in line-length on some of the early Thomson-Houston arc machines, the machine would carry more load. A 50-lamp machine with a long line would often carry 55 arc lamps. Undoubtedly in that machine the inductance of the field windings had a good deal to do with the operation of the machine, and this inductance was added to by a long line. It was a machine which when first sent abroad evoked the opinion that it ought not to work—but did work. One must take into account the fact that although at the commutator during regulation there was a definite short-circuit repeated six times during a revolution, the inductance of the windings kept the current from too great fluctuation.

Mr. Rice has adduced several interesting matters. I remember the instance he has told of in which he had to resort to the use of a supersensitive arc to keep the current stable on the circuit. I also remember very well the condition he referred to in which we had too much of a copper band on the field—the field magnetism did not vary enough. It is well known that in the case of machines of the open-coil type, if the field is maintained and any flashing occurs, such flashing becomes permanent; they can not be used as separately-excited or even as shunt-excited machines.

Mr. Stott has asked about the original three-phase machine. When we first applied for a patent on the three-coil machine, it was illustrated in the patent specification with a commutator and also with slip-rings, as alternatives, since the novelty of the structure was well appreciated; but the Patent Office was unwilling to recognize our arguments with relation to the winding with slip-rings, and to save time we finally gave up and took out the patent with claims for the winding with commutator segments, and left out the slip-ring combination. As shown in the specification originally with slip-rings, it was, of course, an alternating three-phase machine. In 1881, in New Britain, we were experimenting with a machine which had slip-rings. We had carried the terminals of the armature to three slip-rings, in addition to the commutator. The object was to control the sparking of the machine by putting condensers between the commutator segments, and to do that we carried slip-ring connections to condensers outside. We found that the trouble was that the condensers would not live, but go off in a flash.

At the same time we noticed high-frequency effects with the condensers, getting sparks between turns of wire leading to the condensers instead of the current going round. The desirability of having another such machine with slip-rings was discussed, as we knew then that we could transmit power without commutation from one machine to the other machine; but as we were not doing power distribution at that time, and no transmissions were then contemplated, we put the matter aside.

In regard to Professor Jackson's statement with relation to the function of the blower, I quite agree with him that the blower would not work unless we had a spark to blow upon. We must have the terminal spark from the brush forward as the segment leaves the brush so as to be able to knock it out of the way with the air blast, and insert the cold air layer. The residual arc was deflected into a new position. The air blast, acting synchronously with the motion of the segment, would drive the tapering end of the spark away down under the segments of the commutator, air insulated as it was, thus allowing plenty of room to put in the cold air. We may perhaps account for the old anomalous so-called Ball unipolar machine by supposing that it was at first made with the four pole-pieces, and that the stability was not then what it should be. By taking off two of the four pole-pieces, thereby lessening the effect of the field, and increasing the armature reaction, stability was probably secured. It then became necessary to speed up the machine to obtain a fair output. The average arc dynamo speed at that time was something like 700 or 800 rev. per min., but this machine ran up to 1600 rev. per min.

Mr. Green referred to the remarkable effect of rounding the corners of the pole-pieces in the Brush arc machine, thus adding evidence to show that it is properly characterized as a pole-piece machine. The question in regard to the fluctuations of current in the Thomson-Houston machine I have virtually answered by saying that the field-coil circuit itself acts as a high inductance and tends to smooth out fluctuations. There would otherwise be a very ragged current curve. In fact an interrupted current would exist if it were not for the large inductance of the field coils. I may mention that when the closed copper band was put on the field, the current was considerably more fluctuating than when it was not used, as would naturally be expected. The current fluctuation was greater with partial load than with full load, from the fact that during regulation there was a longer interval of short-circuiting with lighter loads.

Mr. Taylor mentioned stability of illumination. That is a little outside of the paper, and it would take some time to discuss it. I do not think we have time to consider the high frequency arc matter now, and its application to wireless telegraphy.

E. A. Sperry (by letter): I was so fortunate as to have been born almost under the eaves of Cornell and was a youth when our late lamented founder, Professor William A. Anthony, was in the midst of his early activities at that institution. It will be remembered that he was the first one to build a Gramme electrical generator in this country, the machine exhibited at the Centennial Exhibition in Philadelphia in 1876. I watched some of the construction of this machine with eager interest, as well as many of the experiments that were tried with it, and some of the overhauling in 1878. I feel that we never have accorded sufficient credit to Professor Anthony. He was a source of inspiration to a great many engineers of the present generation, combining as he did in a most extraordinary degree keen perception in theory as well as wonderful mechanical ability and unusual skill as a pure mechanician.

In 1879, I had built my first dynamo and arc lamp in Cortland, New York, near Ithaca. Then in Syracuse, I completed a 15-lamp machine which in 1880 was taken to Chicago, where we built a plant and started manufacturing a system of arc lighting, which included a regulator by means of which the lamps could be turned on and off. It was shown that a 20-lamp circuit could be cut down to five, and later we found means for reducing a 30-lamp machine to one lamp.

The early machines were all of the short-arc type. We started to build the long silent arc of about 9 amperes in 1884. As I remember, one of the first 6-ampere machines was sent to Cornell for testing purposes. After we were established in Chicago, there came upon the horizon a new lamp, about which I had already quite thoroughly informed myself. The current was supplied by a Thomson-Houston arc-light machine. The first night the lamp started I was present as an observer. I thought at that time the lamp ought to work; there was a case, it seemed to me, of a pulsating current, in which the current supplying the lamp was forced along the line in impulses which were positively divorced from each other, and, through the vigorous shaking and vibrating which the regulator of the arc was constantly undergoing, no wonder the lamp could operate well and feed continuously. With our finely divided commutator and smooth flowing current, however, it was not an easy matter to cause a continuous and uniform feed of the carbons. Before many years the Thomson-Houston system became formidable, and we found great difficulty in maintaining our standard in competition with it. This system was developed by Professor Thomson.

The tests at Cornell in 1885 showed us that the armature reaction and the drooping characteristic of the machine were the secrets of stability and regulation in our machines. But in those days it was a matter very largely of cut and try methods.

About that time I carefully constructed an ammeter and sent it to Charles F. Brush at Cleveland, asking him kindly to mark 9.6 amperes on the scale. Correct measuring instruments were difficult to obtain and even more difficult to keep in calibration.

Chas. P. Steinmetz: The interesting phenomena of instability of electric circuits, discussed by Professor Thomson, have an importance far beyond the arc circuit. Owing to the work of Professor Thomson and other investigators, the arc circuit is the first and therefore the best known type of unstable circuit; but instability occurs frequently also in other electrical and mechanical systems, and the study of the conditions leading to instability thus is one of the most important subjects of electrical engineering. Thus we find that synchronous and induction motors drop out of step, or we find such motors starting from rest, but failing to run up to their proper speed; we meet with surging of synchronous apparatus, and find electrical apparatus misbehaving, apparently without reason, at the end of very long transmission lines.

In all these phenomena, the same characteristic is the cause of instability, which was investigated so ably by Professor Thomson in the early days of the arc circuit. This characteristic is: if the effect of a cause is in opposition to the cause, the system is stable; if however the effect assists the cause, it becomes accumulative, and instability results. When dealing with energy, as a corollary to the law of conservation of energy it follows that the effect always opposes the cause, and thereby limits itself. When not dealing with the question of energy, however, the effect may assist the cause and thus give instability. The typical case is that of an arc in a constant-potential circuit. The voltage consumed by the arc decreases with increase of current. The current depends on the resultant e.m.f., that is, the difference between impressed e.m.f. and the voltage consumed by the arc. An increase of current causes a decrease of the arc voltage and thereby an increase of the resultant e.m.f., hence a further increase of current etc.; that is, instability: either a short-circuit, or extinguishing of the arc.

The cause of this phenomenon is the volt-ampere characteristic of the arc, shown in Fig. 1, as *I*, which decreases with increase of current. Assuming now a metallic resistance r inserted in series with the arc, the voltage consumed by r is shown by the straight line *II* in Fig. 1, and the total voltage consumed by arc and series resistance is curve III. This curve III has a minimum point for a certain critical value of current i_0: above this value, the conditions are stable; that is, an increase of current requires an increase of voltage, and thereby limits itself. Two values of current, i_0 and i_2 thus exist at the same supply voltage, of which the upper one, i_2, gives stability, while at the lower one, i_0, the arc is unstable, and either goes out, or the current increases, until the upper value of current i_2, and thereby stability, is reached.

Similar relations between the arc volts and amperes are frequently met in electrical engineering, for instance in the relation between speed and torque of the induction motor. The speed-torque curve of a polyphase induction motor is shown as *D* in Fig. 2, with the speed as abscissas, the torque as ordinates. Assuming such an induction motor operating on a load requiring a constant torque, as when driving a reciprocating pump

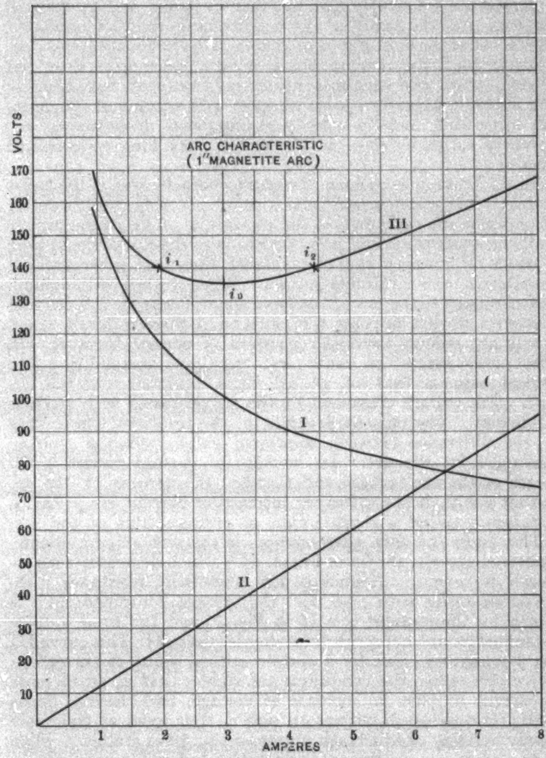


FIG. 1

working against a constant head of water, then in the range between synchronism and the maximum torque point *m*, the speed of the motor is stable. Thus at the load *L*, the speed *c* is 94 per cent of synchronism, and any momentary increase of speed decreases the torque, a momentary decrease of speed increases the torque, and thereby limits itself. The same torque is reached again at a lower speed *d*, of 55% of synchronism. This speed, and the entire range from standstill *t* to the maximum torque point *m*, is unstable; that is, at the point *d*, the motor either drops down to standstill, or runs up to the stable speed *c*, but can not continue to revolve at *d*, on a load requiring constant torque *L*.

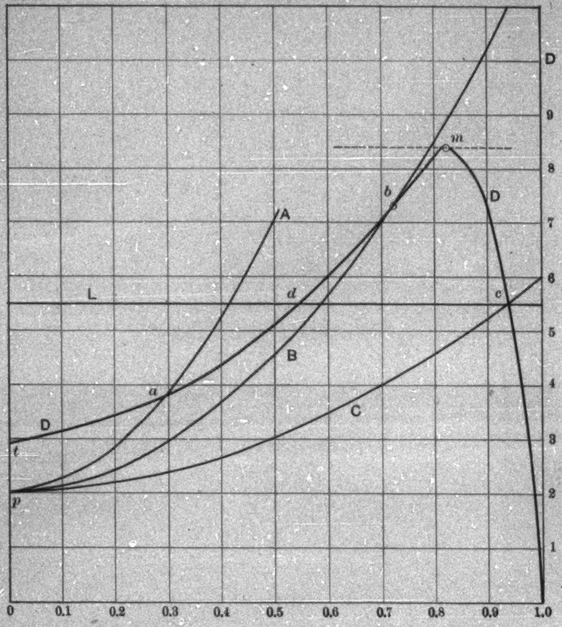


Fig 2

The conditions of stability or instability of induction-motor speed, as discussed here, apply only to the case of a load requiring a constant torque, just as the stability consideration of the electric arc applies only to the case of constant voltage supply. The question of stability of electric and mechanical systems therefore involves two conditions: the circuit or system, and the external conditions under which it is stable or unstable;

that is, in the present instance, the volt-ampere characteristic of the electric arc, and the condition of constant voltage supply; or the speed-torque characteristic of the induction motor, and the condition of constant torque of the load.

Assume for instance a load requiring a torque proportional to the square of the speed, as when driving a centrifugal pump, or a ship propeller. In this case, if the required starting torque *p* (Fig. 2) is less than the starting torque *t* of the motor, the motor always starts and runs up to the speed corresponding to the load: a high speed *c* for moderate loads *C*, a lower speed *b* for overloads *B*, and a low speed *a* for excessive loads *A*; but the speed-torque relation is always stable, that is, with this character of load the induction-motor-torque curve has no unstable branch.

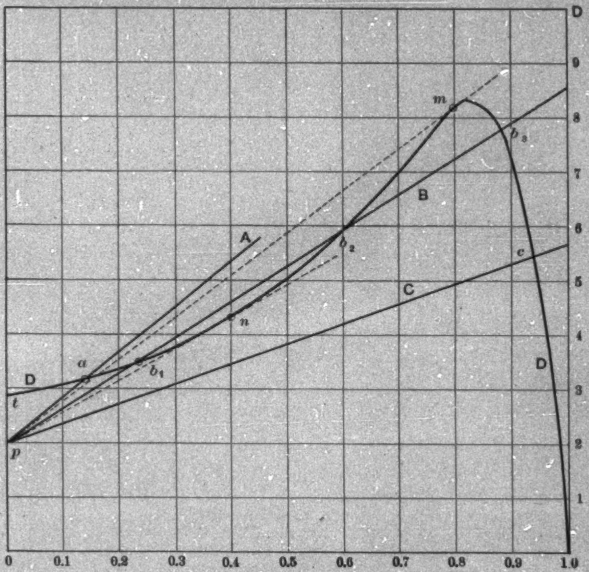


Fig. 3

Still more interesting are the speed-torque relations of the induction motor on a load requiring a torque proportional to the speed, as when driving an electric generator at constant field excitation and loaded by a constant resistance, as shown in Fig. 3. The motor always starts from rest. At moderate load, the speed runs up to near synchronism, on a straight line *C*. At excessive overloads, the motor still starts, but runs up to a low speed *a* only, and keeps revolving in stable condition at this low speed; that is, in a range of the motor curve, which on a load requiring constant torque is unstable. Especially interesting is the case of an intermediary load, represented by line *B* in Fig. 3. *B* intersects the motor curve *D* at three points, b_1, b_2, b_3; that is, three different speeds exist, at which the motor gives the torque required by this load, at 24 per cent, 62 per cent and 88 per cent of synchronism respectively. Of these, the intermediate speed b_2 is unstable, and so is the entire range of the motor curve between the points of contact *n* and *m* of the two tangents from *p* on curve *D*, while the low and the high speed are both stable. That is, if started from rest, on this load, the motor runs up to speed b_1 and stays there. If the load is taken off and the motor is allowed to accelerate near synchronism, and the load then put on again, the motor slows down to speed b_3 and stays there. At speed b_2 however, the motor can not continue to run, but either slows down to speed b_1, or speeds up to speed b_3.

We have here a case where a motor can carry the same load at two different speeds, a high speed, with moderate current—the proper running speed—and a low speed, with excessive current. In this case, the motor operates satisfactorily at speed, it always starts, but it does not run up to its proper speed, and shows a "dead point", or rather a "dead range" at intermediary speed. Phenomena of this character are frequently met with in single-phase induction motors, polyphase synchronous motors etc., though more or less complicated by secondary actions, as the effect of the motor-starting device, the magnetic locking of stator and rotor teeth, the induction machine action of the synchronous machine, etc.

Still a different form of instability occasionally occurs in induction motors. On constant voltage supply and at a moderate drop of speed, frequently far below the maximum torque point, the motor suddenly drops out of step without previous warning. This phenomenon depends upon the relative momentum of the induction motor and its load and of the generating system, and on the rapidity of voltage regulation of the generating system, and may become marked with a sluggish system of voltage regulation.

Of special interest also are different forms of instability which lead to surging of synchronous machines, as the surging due to electromechanical resonance, which is frequently eliminated by lowering the motor excitation, that is, running with lagging current, while the surging due to the limited power supply of the generating system is intensified by lowering the motor field excitation, that is, running with lagging currents, and may disappear with over-excitation of the motor and operation with leading current. The study of these phenomena is of the highest importance, as apparently the same phenomena may be produced by entirely different conditions, and the remedy in one case thus may intensify the troubles in another case which resulted from different conditions. However, the subject is too vast to be dealt with in a short discussion, but may form a separate paper.

An interesting feature of the Brush arc machine is the great constancy of current independent of speed fluctuation: even speed variation of 50 per cent or over with such machines does not appreciably vary the current, but merely reduces the maximum voltage of the machine and thereby its output in proportion to the speed reduction. It is startling to observe in such a machine, at light load, when shutting it down, how perfectly constant the current remains even down to speeds of a very small percentage of normal and until the very moment when the machine stops.

Another type of arc machine, a constant alternating-current generator, deriving its constancy of current from armature self-induction, was once introduced into the industry, the Stanley constant-current alternator. This was afterwards modified by the addition of a rectifying commutator into a constant direct-current arc machine, but disappeared after some years, apparently owing to the unsatisfactory character of the arc lamps operated from it. It would therefore be of interest to hear something of this development of by-gone days.

Similar to the interesting case of the induction motor, above discussed, conductors which can carry the same load at three different speeds are occasionally met with. Thus for instance there are conductors among the so-called "pyro-electrolytes", which at the same constant-supply voltage can pass three different currents. The volt-ampere characteristic of one such conductor, a magnetite chromite alloy, is shown in Fig. 4. As seen in Fig. 4, at the same voltage, as 20 volts, the current can have three different values $i_1 = 0.45$; $i_2 = 5.0$; $i_3 = 36$ amperes.; and of these three values, the low one, i_1, and the high one, i_3, are stable, the middle one, i_2, with the entire range of the curve, between maximum m and minimum n, is unstable.

However, even the volt-ampere characteristic of the arc is not always the curve shown in Fig. 1, but may be considerably modified.

This curve in Fig. 1 is fairly well represented by the equation:

$$(e - a)^2\, i = \text{const.}$$

but applies only to the arc at constant vapor pressure, as the arc in air. A different volt-ampere characteristic results, if the vapor pressure in the space in which the arc is produced varies with the current, as for instance is the case with a vacuum arc, as the mercury arc. Thus the volt-ampere characteristic of the mercury arc in stationary conditions is of the character shown in Fig. 5, that is, has a range of minimum voltage at intermediate currents, while for smaller currents as well as for larger currents the voltage increases. Especially interesting is the latter range for larger currents, where an increase of current requires an increase of voltage. From our previous considerations, such a characteristic should give stability on constant-potential supply; that is, for currents above the minimum voltage range, the mercury arc should be capable of operating steadily on constant-potential supply, without any series resistance, by any variation of current limiting itself. This however is not the case, but the mercury arc in a vacuum is unstable on constant potential over the entire range, just as any other arc is, and for the same reason that an increase of current causes a momentary decrease of voltage and thereby becomes accumulative. Thus, in the mercury arc of Fig. 5, an increase of current from 5 amperes to 7 amperes raises the voltage consumed by the arc from 33.2 to 36.6. In the first moment, however, after raising the current from 5 to 7 amperes, the voltage drops, as indicated in Fig. 5 in dotted lines, to about 30 volts for a short time, a few seconds, but still long enough to be observed by the voltmeter, and then gradually, during some minutes, increases to its stationary value of volts. This leads to the distinction between the volt-ampere characteristic of the arc, shown in Fig. 5, and the momentary volt-ampere characteristic, and it is the latter which determines stability or instability. The latter is always dropping, and thus the arc is always unstable on constant potential.

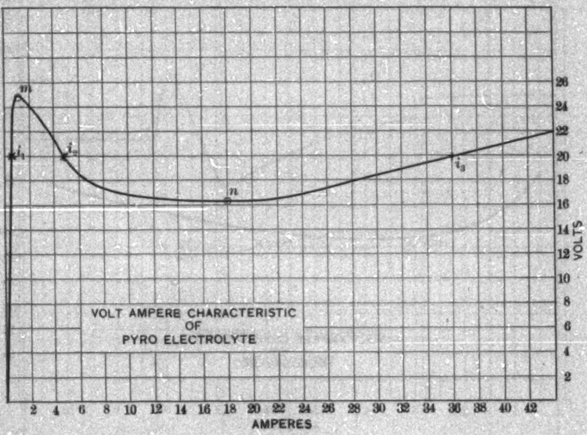


FIG. 4

In reality, the period of voltage drop with increase of current is preceded by an extremely short period of voltage rise; that is, with an increase of current in the mercury arc, the voltage first rises, then drops, and then gradually rises to the final value, about as shown in Fig. 6. The first period of high voltage lasts for a thousandth of a second or less, but may be observed under favorable conditions by the oscillograph. It is the conduction through the vapor stream of previously existing lower current. With a velocity, possibly of some thousand feet-seconds, the conducting vapor stream of the arc adjusts itself to the change of current and hence drops in resistance. The arc voltage thus decreases approximately by the above equation $(e-a)^3 i =$ constant. The vapor pressure in the space rises gradually and the resistance of the arc stream thereby increases and thus also the voltage. With an arc in enclosed space, the second period of low voltage thus lasts a few seconds only, while with arcs at constant pressure, as in air, it is the permanent condition, and the third period is never reached.

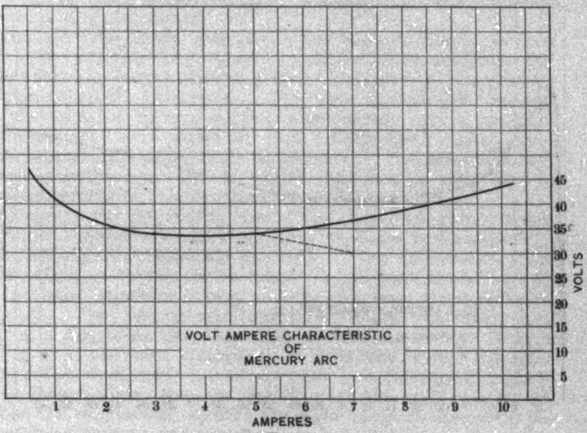


FIG. 5

The initial period of very short duration, where the arc conductor has not yet reached the stationary condition corresponding to the current flow, can be observed indirectly by superimposing on a direct-current arc a small high-frequency current and gradually increasing the frequency of the latter. Ultimately then a frequency is reached where the power-factor of the superimposed alternating current is unity; that is, the arc stream acts as ohmic resistance, or in other words, the variations of current are faster than they can be followed by the vapor stream of the arc. This transient period of the arc is of very great industrial importance. Extending back the arc characteristic Fig. 1, it must intersect the zero line of current at the disruptive voltage; that is, the voltage required to jump a spark across the terminals. If then the arc is started by a spark, the volt-ampere characteristic traverses a curve starting with the disruptive voltage at the moment of the passage of the spark, and rapidly decreasing in voltage with increase of current. This transient

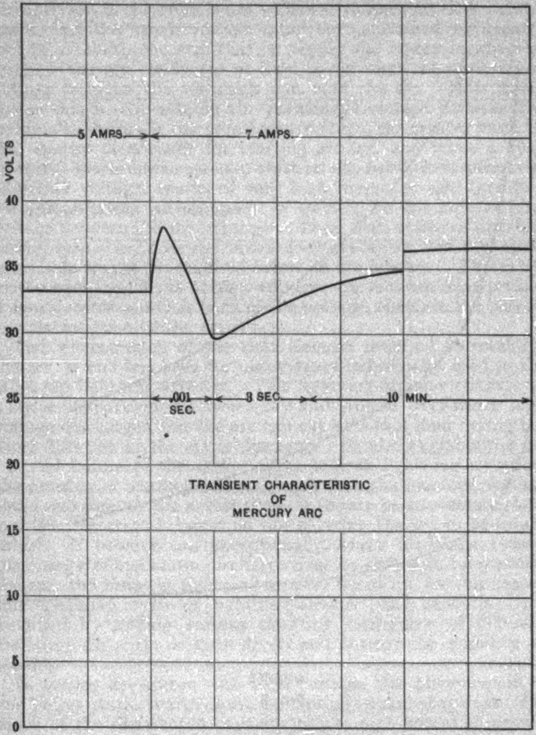


Fig. 6

volt-ampere characteristic however is not the curve in Fig. 1—which is reproduced as *I* in Fig. 7—but is higher; the more so the more rapidly the current increases, as shown by II and III in Fig. 7. In consequence thereof, if the high voltage lasts only a very short time, that is, decreases very rapidly, the voltage may fall below that required by the transient arc characteristic, and

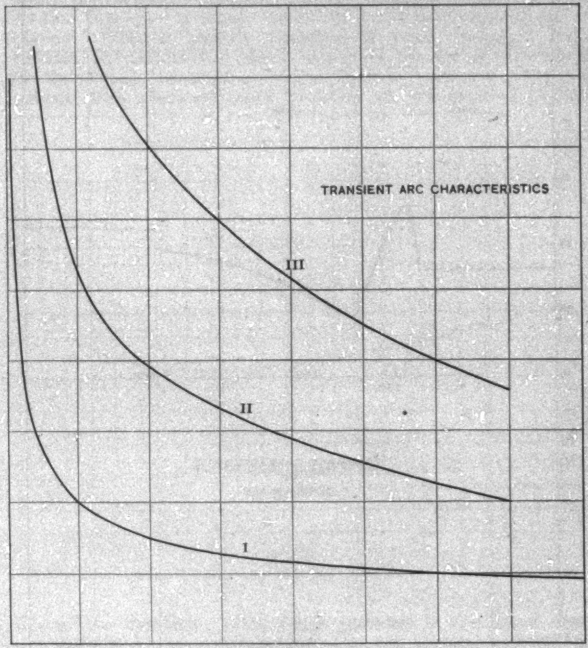


Fig. 7

the arc goes out, or in other words, will not be established by the electrostatic spark, even if the voltage between the terminals is sufficiently high to maintain an arc when once established. This is the explanation of the phenomenon that a static spark between terminals is not always followed by an arc, even if the voltage at the terminals is sufficiently high to maintain an arc when once established. Thus, while it requires about 100 volts to maintain an arc between terminals one inch apart, with 2000 volts potential difference between these terminals, static sparks may be jumped across these terminals, without any arc following if the duration of the voltage which sends the spark across the terminals, is less than the time required for the transient arc characteristic in Fig. 7 to drop to 2000 volts. To start an arc disruptively, it therefore is not sufficient to have an electrostatic spark, but the spark voltage must be maintained sufficiently long to establish the arc; that is, supply the power required to produce the arc conductor at least so far that the maintained voltage between the terminals can hold the arc. How much power this is, depends on the permanent voltage between the terminals: the lower the permanent voltage, the greater must be the energy of a spark for starting an arc, and while a very powerful spark discharge may start an arc between terminals of moderate voltage, sparks of very high frequency and therefore very small power are incapable of starting an arc even at high voltage between the arc terminals. Thus, with sparks of such low power, insulation does not break down instantly, but numerous successive sparks are required before an arc follows. This is the reason why the effects of high voltages are so much more severe, if considerable power is back of the voltage, than are the powerless discharges of static machines.

This phenomenon of the time element required to establish the arc, is and has been for many years industrially used in the multigap lightning-arrester. This lightning-arrester consists of a series of spark-gaps between line and ground, over which high voltage discharges, but the arc can not be established during the short duration of the static discharge. It also explains the occasional failure of the earlier types of such lightning arresters, the number of spark-gaps being such that the machine voltage could maintain an arc across them, if the arc be once established, and the operation is based on not allowing the arc to be established. If however an exceptionally heavy discharge passes, the energy of the static discharge may be sufficient to establish the arc, and then the lightning-arrester burns up; for this reason this multigap type of lightning-arrester has recently been modified by adding various shunting resistances of different discharge capacity, so as to divert and destroy the stability of the arc.

In testing apparatus with high voltage, this phenomenon of low power static sparks must be carefully guarded against. Because of the distributed capacity of the high-potential circuit, oscillations of very high frequency are produced, which, superimposed on the permanent alternating testing voltage, cause sparks to jump across the testing spark-gap long before the permanent voltage has reached the required values, and thus long before the specified insulation strain has been reached. In using a spark-gap in high-voltage testing, it is therefore necessary to insert resistances in series or in shunt to eliminate such oscillations. A discharge of the spark-gap indicates the existence of the required test voltage, only if the spark is followed by an arc, but not otherwise. Thus I have seen sparks jump a one-inch gap, with the static voltmeter indicating only 10,000 to 12,000 volts, and by raising the voltage of the step-up transformer the voltage indicated by the static voltmeter remained the same, but merely the frequency of the sparks increased, without however an arc following. As soon as an arc follows, the static voltmeter instantly drops to zero: short-circuit.

Elihu Thomson. It is gratifying that the paper served to get Dr. Steinmetz on his feet. We always learn a great deal from his discussions. May I suggest that it would be a capital idea for him to present a paper on other forms of instability. He has given half a promise that he would do this.

I agree with Dr. Steinmetz that it is a large subject and one can approach it from various sides. I have dealt with the most decided example of instability, the arc circuit, where all the conditions tend to instability, and effective provision has to be made to avoid instability. The other conditions Dr. Steinmetz has alluded to in the discussion are of course in similar lines, very suggestive indeed, and I think should be followed out. We should have a good exposition, such as I know he can give us, of the different forms of instability depending not only on the current, but instability of torque and speed, etc. There is, in fact, material here for several good papers.

Following Dr. Steinmetz we see the reason why it has been very difficult to work arcs of very small current value. They must exist if at all on the very steep part of the characteristic curve, and require high voltage and potent influences to secure stablilty.

Dr. Steinmetz has pointed out the fact that there is an instantaneous effect before settling down, when a change is made in the current strength in an arc. He shows that this effect is in fact in an opposite direction to that which is the final result, and without doubt has indicated the true reason of the effect, in the time it takes for the shift in the volume of the arc stream or hot gases to take place. On an increase of current a slight excess energy must be absorbed while the arc is expanding, and this can only occur with a momentary increase of opposition measured as a resistance.

A paper presented at the Cleveland Section of the American Institute of Electrical Engineers, February 8, 1909.

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THE PURCHASE OF FUEL ON A BRITISHTHERMAL UNIT BASIS[1]

BY LAWRENCE P. CRECELIUS

The boiler plant of the traction company which operates the street-car system of Cleveland, Ohio, is representative of modern practice in both the nature of the equipment installed and the means employed in handling and firing coal. Of the total cost of manufacturing a kilowatt-hour in this plant, exclusive of investment charges, taxes and insurance, the fuel item amounts substantially to 70 per cent. The calorific value of the fuel used is obviously of the utmost importance, and to insure a supply of coal having a high thermal value is therefore greatly to be desired. This may be accomplished by making use of one of three means which are at our command:

First, to locate the power plant at the mine where good coal lies; second, to bind by contract the supply from certain districts or mines producing coal of known heat value; and third, to purchase coal on a calorific value basis.

The heat efficiency of the power plant referred to in this paper is approximately eight per cent; this means that out of every 100 tons of coal burned, the energy of but eight tons is delivered to the switchboard in the form of electricity. Probably the greatest factor entering into the cost of coal in the United States is the cost of transportation, and as this could be entirely eliminated by locating the power plant at the mine this plan seems attractive. Most unfortunately, however, this is impossible as yet, not so much on account of the geographical limitations as of physical conditions. The second plan, which probably is in general use, and no doubt will continue for some time to be employed, was the method by which coal was purchased for this power plant. This plan, however, proved unsuccessful, mainly owing to the fact that both goo dand poor coals exist in the same district or mine, and also because stock coal could be sent in on this contract.

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[1] The author acknowledges with thanks the work of Messrs R. W. Emerson and E. H. Haynes in calculating and experimenting to ascerain the values contained in this paper.

The method of purchasing coal on the basis of calorific value has finally been adopted and with very satisfactory results. Payment is made only according to the B.t.u. contained in the coal, and suitable restrictions are imposed on the maximum amount of ash and sulphur which the coal may contain.

Ohio bituminous slack, of a heat value of 12,500 B.t.u. and with 15 per cent ash and 3.5 per cent sulphur per pound of dry coal, has been specified in the contract because of its relatively low cost, although, at the time when this contract was drawn up it was necessary to take local conditions into consideration to such an extent that the table was made flexible enough to make it possible to supply coal from other districts on the same table. It may be interesting to note that while the purchasing of fuel on a calorific value basis has been attended with good results, it was prompted by a different cause than that which brought about this practice in New York City. There, the predominating influence which effected its introduction, as the writer understands, was to restrict the volatile matter contained in the coal, on account of the stringent smoke regulations.

Here, upon the threshold of two great coal-producing districts, with a difference in freight rate from them to this city and with a considerable difference in the price of the coal from the two districts, it occurred to the writer that some severe restrictions must be placed upon the quality of coal sent in. The city of Cleveland has in effect a heat-value contract under which is purchased the slack required by the Water Department. The heat value of the coal is placed rather high and the coal is required to be up to or above this standard when the contract price is paid. But for coal running less in heat value than that called for by the contract, a deduction in price is made in proportion to the amount less than the standard. Aside from this, however, no information was at hand or available, as far as the writer knows, covering the purchase of slack on a heat-value basis. The case of the Interborough Rapid Transit

Company of New York and several others within the writer's knowledge covered a very high grade of fuel, and, therefore, a good many allowances had to be made in the nature of restrictions which should be imposed upon the amount of fixed carbon, volatile matter and moisture contained in the coal. In lieu of this the company abandoned the idea of placing a premium upon a certain minimum of ash in the coal.

Early experience with the grade of fuel to be supplied under the heat-value contract had shown that coal which runs high in heat value is usually low in ash, sulphur and moisture, so it became only necessary to limit the coal to the maximum permissible amount of ash and sulphur; subsequent experience has confirmed this hypothesis.

A point worthy of being mentioned here is that the standard in the contract has been made rather low. This was done in order to get a low basic contract price, for when it is understood that premiums and penalties are of an accelerating rate on either side of the standard, and based on the contract price, it may be better understood. As a matter of fact it was expected to pay slightly more than the prevailing contract price of slack as a guaranty of good coal, and in the light of the contrast with the quality of coal received under the old contract in force prior to the inauguration of the purchase of coal on the heat-value basis, this policy has been justified.

Another point of interest, and one which has a very marked influence on the success or failure of this kind of contract, is the personality of the coal dealer. Only the most responsible parties should be dealt with.

There are available in the Cleveland market in extensive quantities two principal grades of bituminous slack, one coming from the Western section of Pennsylvania, the best of which is known as Youghiogheny gas slack, and the other from the Eastern part of Ohio.

For a period of about two months before the contract was put into effect, the company made a series of evaporative tests to determine the relative steam-making qualities of Ohio bituminous slack and Youghiogheny gas slack. These tests clearly indicated that in the furnaces as constructed, and with the draft available, both Youghiogheny slack and Ohio slack can be burned with equally good results. Average chemical properties of the two kinds of slack, per pound of dry coal, are as follows:

	Youghiogheny gas slack.	Ohio bituminous slack.
B.t.u.	13,185	12,614
Ash	11.6%	13.8%
Sulphur	2.03%	3.53%
Volatile combustible matter	31.95%	36.62%
Fixed carbon	53.52%	45.55%

The relative evaporation per pound of coal as fired was 7 per cent in favor of the Youghiogheny gas slack. The inherent moisture contained in the coal in the first case is 1.52 per cent and in the second case 2.7 per cent.

Basis upon which payments are to be made. In order to illustrate the work of sampling shipments of coal received, and to describe how adjustments of any disputes which may arise between the contracting parties are made, the section of the contract relating to these matters is herewith reproduced. This general method was devised and put into effect by the Interborough Rapid Transit Company of New York, a few years ago, and the essential features, modified to suit local conditions, have been adopted by the traction company.

Each day's consignment of coal furnished to each power plant by the contractor during the continuation of the contract, is sampled by the superintendent or his authorized agent and analyzed to determine its heat value, and the price paid by the company, per ton, for each car of coal is based on a table of heat values in excess or deficiency of the standard therein contained, but subject to further deductions for ash and sulphur.

A small quantity of coal is taken from at least five different places in each car received, by driving into the coal a five-foot ram (Fig. 1), before the car is unloaded. The quantities thus received from each car of coal of the day's consignment are thrown into a receptacle provided for this purpose, and thoroughly mixed, and a properly selected sample of this mixture is taken for chemical analysis. One-half of the sample of the average mixture is labeled and held at the company's laboratory for a period of two weeks after unloading the cars. The other half of the sample taken from the average mixture is analyzed as soon as possible after being taken. No other sample is recognized.

Tests of the sample taken from the average mixture are made by the company's chemist under the supervision of the superintendent. Should the contractor question the results of the company's test, a copy of which is mailed to him, the company will, if requested within three days after the copy of test has been mailed, forward the other half of the sample, held for this purpose, to any laboratory in the city of Cleveland which may be agreed upon by the superintendent and the contractor, and have the said sample analyzed by it, and the results obtained from this second test shall be considered as conclusive and final. In case the disputed values, as obtained in the company's test, shall be found by the second test to be two per cent or less in error, then the cost of the second test shall be borne by the contractor; but if the disputed values shall be found to be more than two per cent in error then the cost of the second test is to be borne by the company.

Should there be no question raised by the contractor within the three days specified as to the accuracy of the company's analysis, the second sample of coal is destroyed at the end of two weeks from the date of unloading the cars from which it was taken. Should a second test be made of the sample of the average mixture, as provided, any penalties to be made will be based on the results as obtained from the second test.

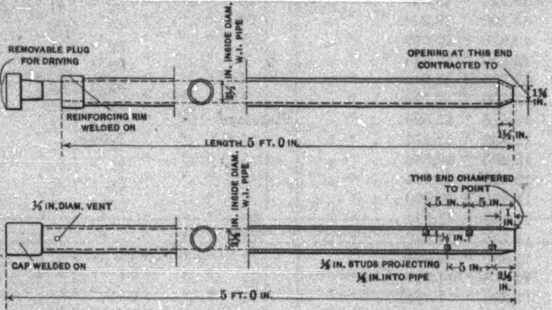
REMOVABLE PLUG FOR DRIVING
2½ IN. INSIDE DIAM. W.I. PIPE
OPENING AT THIS END CONTRACTED TO
1¾ IN.
REINFORCING RIM WELDED ON
1½ IN.
LENGTH 5 FT. 0 IN.
2½ IN. INSIDE DIAM. W.I. PIPE
THIS END CHAMFERED TO POINT
½ IN. DIAM. VENT
5 IN.
5 IN.
1 IN.
¼ IN.
CAP WELDED ON
¾ IN. STUDS PROJECTING ¼ IN. INTO PIPE
5 IN.
2½ IN.
5 FT. 0 IN.

FIG. 1—Slack sampling rams at the Viaduct and Cedar avenue power stations

Penalties for excess ash and sulphur. Coal which is shown by analysis to contain less than 15 per cent of ash and 3.5 per cent of sulphur is accepted without a deduction on that account. Where the analysis gives amounts of any neutral elements in excess of these quantities, deductions are made from the basic contract price in accordance with a schedule provided, independent of the corrections made for departures from the standard B.t.u. value.

It will be noticed that each day's consignment of coal delivered to each power plant is analyzed, instead of each individual carload of coal, although a sample is taken from each car. The object of this plan is to obtain an average of the whole day's supply in order to allow the dealer the benefit of cars of coal running low in ash and sulphur offsetting those running high.

PREMIUMS AND PENALTIES.

For coal in any car which is found by analysis to contain per pound of dry coal

13,975 and above	35 cents per ton above standard
13,850 to 13,974, inclusive—	35 " " " " "
13,725 " 13,849 "	30 " " " " "
13,600 " 13,724 "	25 " " " " "
13,475 " 13,599 "	21 " " " " "
13,350 " 13,474 "	17 " " " " "
13,225 " 13,349 "	13 " " " " "
13,100 " 13,224 "	10 " " " " "
12,975 " 13,099 "	7 " " " " "
12,850 " 12,974 "	5 " " " " "
12,725 " 12,849 "	3 " " " " "
12,600 " 12,724 "	1.5 " " " " "
12,475 " 12,599 "	Standard
12,350 " 12,474 "	1.5 " " " below "
12,225 " 12,349 "	3 " " " " "
12,100 " 12,224 "	5 " " " " "
11,975 " 12,099 "	7 " " " " "
11,850 " 11,974 "	10 " " " " "
11,725 " 11,849 "	13 " " " " "
11,600 " 11,724 "	17 " " " " "
11,475 " 11,599 "	21 " " " " "
11,350 " 11,474 "	25 " " " " "
11,225 " 11,349 "	30 " " " " "
11,100 " 11,224 "	35 " " " " "
10,975 " 11,099 "	40 " " " " "
10,874 " 10,874 "	45 " " " " "
10,725 " 10,849 "	50 " " " " "
10,600 " 10,724 "	55 " " " " "
10,475 " 10,599 "	60 " " " " "
10,350 " 10,474 "	65 " " " " "
10,225 " 10,349 "	70 " " " " "
10,100 " 10,224 "	75 " " " " "
9,975 " 10,099 "	80 " " " " "

9,975 and below, an additional 10 cents per ton per car will be deducted for each one per cent variation below standard.

The plan also offers the advantage to the company that, on account of having a fewer number of samples to analyze, the chemist is not hurried in his work and can therefore devote more attention to the preparation of samples and to the checking of his determinations.

The table of allowances referred to in this section of the contract is so proportioned as to incite the dealer to supply Ohio bituminous slack of a value ranging from 12,500 B.t.u., the standard in the contract, to 13,125 B.t.u., 5 per cent above the standard; this range gives him the best profit obtainable. In order to guard against the supply of fuel having a high B.t.u. value, but which, by reason of its chemical composition, is not well adapted to the stoker equipment, a limit has been set above which no further premiums are paid.

DEDUCTIONS ON ASH.

00.0 to 15%, inclusive—	Standard
15.1 " 16 "	3 cents below standard, per ton
16.1 " 17 "	6 " " " " "
17.1 " 18 "	9 " " " " "
18.1 " 19 "	12 " " " " "
19.1 " 20 "	15.5 " " " " "
20.1 " 21 "	19 " " " " "
21.1 " 22 "	22 " " " " "
22.1 " 23 "	25 " " " " "
23.1 " 24 "	28 " " " " "
24.1 " 25 "	31 " " " " "
25.1 " 26 "	34 " " " " "
26.1 " 27 "	37 " " " " "
27.1 " 28 "	40 " " " " "
28.1 " 29 "	43 " " " " "
29.1 " 30 "	46.5 " " " " "

DEDUCTIONS ON SULPHUR.

0.0 to 3.9%, inclusive—	Standard
4.0 " 4.4 "	2 cents per ton below standard
4.5 " 4.9 "	5 " " " " "
5.0 " 5.4 "	7 " " " " "
5.5 " 5.9 "	9 " " " " "
6.0 " 6.4 "	12 " " " " "
6.5 " 6.9 "	14 " " " " "
7.0 " 7.4 "	16 " " " " "
7.5 " 7.9 "	19 " " " " "
8.0 " 8.4 "	21 " " " " "
8.5 " 8.9 "	23 " " " " "
9.0 " 9.4 "	26 " " " " "
9.5 " 9.9 "	28 " " " " "
10.0 " 10.4 "	30 " " " " "

To guard against a supply of low-grade cheap coal or slack which has been kept in stock, the B.t.u. value table is so arranged that the value can fall but 10 per cent below standard, where by reason of the addition of penalties due to ash and sulphur on this sort of fuel, the price is cut to such an extent that only the freight charges are realized.

Almost immediately after the contract went into effect, a marked improvement in the cost efficiency of the entire plant took place, accompanied by an improvement of some eight per cent in the consumption of coal per kilowatt hour.

In conclusion it may be said that the installation of the scheme of purchasing fuel on a heat-value basis has been justified.

Taking samples. In the preceding paragraphs reference has been made to a ram by means of which samples are taken from the car. The efficiency of the ram when used for this purpose is indicated by the table below.

	Sample taken by hand at regular intervals while car was being unloaded.	Sample taken from top of car.	Sample taken by means of ram.
Wt. of sample......	600 lbs.	20 lbs.	20 lbs.
B.t.u..............	12,843	12,918	12,777
Ash...............	10.96%	10.4%	11.3%
Sulphur............	2.51%	2.53%	2.56%

A sample obtained in instalments during unloading, taken with great care and diligence, may be said to be truly representative of the entire contents of the car. It was, however, soon found to be unsatisfactory in practice as the men, when unloading cars, unless closely watched, would take enough coal at once, in order to get through with the job as soon as possible.

The sample obtained by ram is shown to be very satisfactory, and owing to the fact that the human element involved is cut to a minimum, fairly accurate samples can be easily and quickly secured right after the cars are placed by the railroad company.

Description of analytic work in laboratory. After the coal in the cars has been sampled and ground up into coarse particles, it is brought to the laboratory for analysis. About 2 pounds of the sample from each car are thoroughly mixed with a large spatula, in order to obtain a fair average of the whole day's shipment. Slack coal and run-of-mine are not mixed, however, but treated as separate samples. The mixed coal is now quartered down until about 0.5 pound of the original amount is left. This part is again mixed, spread out in a thin layer and about 20 to 25 grams of it removed from various points with a small spatula, to be used as the sample for analysis. The remainder is put away in an air-tight sample can, properly labeled for future reference. The smaller part is ground repeatedly with a muller and bucking board until the whole will pass through a 100-mesh sieve. The pulverizing and sifting thoroughly mixes the sample, which is put into the heater for one hour at a temperature of 100 degrees cent. The heater consists of a copper oven surrounded by a water jacket, in which the water is kept at a boiling temperature by a bunsen burner. The coal, now dried out, is ready for analysis. Sulphur, ash and British thermal units are the constituents usually determined—although moisture and volatile combustible matter are sometimes required for boiler and stoker tests.

Sulphur determination. For the sulphur, 0.5 gram of the dry sample is weighed. Two determinations are carried on simultaneously on each sample, in order to have a check on the results. The 0.5 gram of coal is put into a 20-gram platinum crucible half-filled with Eschka mixture, then stirred together, covered with a little more of the mixture and placed over a bunsen flame turned very low for fifteen minutes. Eschka mixture consists of two parts (by weight) of calcined magnesium oxide, (MgO) and one part (by weight) of dried sodium carbonate, (Na_2CO_3). At the end of 15 minutes the flame is gradually turned up to full power, and the mixture heated for 45 minutes, meanwhile being stirred several times. After the whole has been fused and the coal completely burned out, the contents are turned into a clean beaker, that part of the fusion adhering to the crucible being washed out by means of distilled water and a rubber-tipped stirring rod. 50 c.c. of distilled water are added to the beaker, the whole allowed to boil for a minute on the hot plate, then filtered through a single filter (Munktell 9 c.m.), the precipitate washed with distilled water, 15 c.c. of 1 to 1 hydrochloric acid (HCl) of specific gram, 1.19 added to the filtrate, the solution boiled for a minute and stirred, then 10 c.c. of saturated barium chloride solution ($Ba\ Cl_2$) added, and the resulting precipitate of barium sulphate ($Ba\ SO_4$) allowed to settle for two hours or longer, while the beaker rests on the hot plate. When settled, the precipitate is filtered off, (using double filter papers), and washed three times with hot distilled water. The filters are then folded around the precipitate, both placed in a clean platinum crucible, and heated over the bunsen flame until burned out. This takes about half an hour. From the weight of precipitate found is subtracted the weight of $Ba\ SO_4$ obtained as the average of two or three blanks previously run on the Eschka mixture. The corrected weight of sulphate is doubled, (as but 0.5 gram of sample was taken), multiplied by 0.1373—the sulphur factor—

and then by 100 to obtain the percentage of sulphur in the coal sample. A sulphur table for half-gram weights is then furnished for reference, thus saving time in figuring results. With six burners and six crucibles at hand, six determinations on three samples of coal are carried on at one time.

Ash determination. When the fused mass in the foregoing sulphur determination has been removed from the crucible, the latter is thoroughly washed out, and in it is placed a gram of the dried coal, accurately weighed for the ash determination. This consists in merely allowing the coal to completely burn out over a full bunsen flame. Sometimes the sample is heated to constant weight, but if burned for two or three hours with frequent and careful stirring, the extra weighing is unnecessary. From the weight of residue found, the percentage of ash in the sample is calculated in the usual way. A half-gram of sample may be used instead of the whole gram, though any error is doubled in this way. Two determinations are made at a time on one sample, and they should check within 0.2 per cent.

While the samples are being heated in the crucibles for sulphur and ash, the B. t. u. determinations are made.

British thermal unit determination. This is accomplished with a Parr calorimeter, which measures the rise in temperature of 2 liters of distilled water, due to the heat absorbed from the combustion of a fixed amount of coal sample with an oxydizing agent. This combustion takes place in a metal bomb, which is immersed in the water, and caused to rotate at about 100 rev. per min. by a small motor. The coal and oxydizing agent are made to combine by passing a current from a 40-ampere-hour storage battery, giving 6 volts, through an electric fuse in the bomb mixture. The fuse wire is of german silver, No. 36, which melts on passage of the current and starts combustion of the coal. The water used in the calorimeter for the heat absorption is protected from outside heat influences by two fibre tubs with air spaces between.

To determine the heat units in a sample of coal, the bomb is first taken apart, all the parts washed and thoroughly dried, and the fuse-wire fastened to the inside terminals in the form of a loop. 0.5 gram of potassium chlorate ($K Cl O_3$) and 0.5 gram of coal sample are weighed and placed in the bomb. To this is added a measure (10 grams) of dry sodium peroxide ($Na_2 O_2$). The bomb is now put together, screwed tight with a wrench, well shaken, the water veins adjusted, then immersed in the 2 liters of water, and made to rotate slowly to secure uniform temperature by the circulation of the water. After about three minutes, the temperature of the water is read from a Fahrenheit scale thermometer inserted through the cover of the calorimeter. The thermometer is calibrated in twentieths of degrees, but the readings are estimated, with the aid of a magnifying glass, to hundredths. After the mercury column has become stationary, the charge in the bomb is exploded, and the thermometer carefully watched, as the mercury rises, until the maximum temperature is reached. The difference between the first reading of the thermometer and the last reading is the rise due to the heat absorbed by the water.

A rise of 0.014 degrees fahr. is due to the heat of the fuse wire used, and a further rise of 0.171 degrees fahr. is caused by the accelerator ($K Cl O_3$). The sum of these two (0.185) is subtracted from the total rise in degrees, and the remainder is multipled by 3117 to obtain the number of heat units in the sample.

The number of heat units is the number of grams or pounds of water that 1 gram or 1 lb., respectively, of coal sample during combustion, will cause to rise 1 degree fahr. in temperature.

The above factor, 3117, is obtained in this way: the 2000 c.c. of distilled water used in the calorimeter weighs 2000 grams; the metal bomb and metal containing-cylinder and pivot together are the equivalent of 135 grams of water on the basis of heat absorption. 2000 grams plus 135 grams gives 2135 grams. This number multiplied by the rise in degrees would give the number of gram calories in fahr. degrees given off when 0.5 gram of coal was burned. Therefore, twice this amount represents the calories of heat from 1 gram of coal. It has been experimentally determined that when coal, $K Cl O_3$, and $Na_2 O_2$ are exploded, only 73 per cent of the heat evolved is due to the combustion of the coal. $2135 \times 2 \times 0.73 = 3117$, which represents the number of gram calories due to a rise of 1 degree.

After each explosion, the bomb is washed out, dried, and wired for the next charge. The 2 liters of water used should be about 4 degrees lower than the temperature of the room, and fresh distilled water is used for each explosion. Two determinations for heat units are always made on each sample, and should agree closely. If the rise in temperature in one case varies more than 0.02 of a degree with the rise on another explosion of the same sample, (corresponding with 62 heat units) then successive determinations are made on this coal until a check or a good average is obtained. A calorific table does away with the calculation and results are obtained directly.

Moisture determination. To find the moisture content the coal in question is first air-dried, a gram of it is weighed, placed in the heater at 104 degrees cent. for one hour and weighed again. The loss in weight divided by the weight of air-dried coal gives the percentage of moisture.

Volatile combustible matter determination. For finding the percentage of volatile combustible matter in coal, a 1 gram sample is placed in a clean weighed platinum crucible, the cover is put on tightly, and the coal heated over the strongest heat of a bunsen burner for three and one-half minutes. At the end of this time the bunsen flame is removed and a blast lamp put under the crucible, care being taken to have a flame below the crucible while making the change, so the contents will not cool. The coal is heated by the blast lamp for three and one-half minutes more, the crucible is allowed to cool in a desiccator and weighed. From the loss in weight from heating, the weight of moisture found is subtracted, and the difference divided by the weight of the sample taken to find the percentage of volatile combustible matter. This difference also contains one-half the sulphur, and this value, found in another determination, is subtracted, leaving the per cent of volatile combustible matter.

Fixed carbon determination. Remove the cover and burn off the remaining carbon over a bunsen burner until nothing remains but the ash—the loss is fixed carbon with the remainder of the sulphur.

Coke and ashes are analyzed in much the same way that coal is, except that tests for sulphur and moisture are not required. In determining the heat units, however, it is difficult to get an explosion with the ordinary chemical, so the use of benzoic acid is resorted to. 0.5 gram of $KClO_3$, 0.25 gram of coke or ash sample, 0.25 gram of benzoic acid (C_6H_5COOH), and 10 grams of Na_2O_2 are used for each charge. A correction must be made not only for the wire and accelerator, but also for the benzoic acid. This correction is found by running two or three blanks of 0.25 gram $KClO_3$, 0.25 gram acid and 10 grams Na_2O_2 for each lot of chemicals and taking the average. From the total rise in degrees after the explosion of coke or ash sample, the blank correction is first subtracted, and the remainder multipled by 6234 (2×3117, as but 0.25 gram of sample instead of 0.50 gram was used) to obtain the number of heat units. For the determination of ash in coke or ashes, but 0.50 gram is taken, as the combustion is slower with these substances.

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PRIME MOVERS

BY CHARLES P. STEINMETZ

I.

Electric energy is not a primary energy; that is, it is not found in nature nor directly producible to any appreciable extent from the stores of energy available in nature—water power and the energy of fuel. To become available for conversion into electric power, the energy found in nature must first be converted into mechanical rotation by some form of prime mover. The engineering characteristics of these converting apparatus may be classed under two main groups, those referring to economy and reliability, respectively. In both, the electric machine, whether generator or motor, ranges very high: its efficiency is virtually unity; its size, first cost, and maintenance small; its reliability great. In the cost of electric power the electric machine plays only a subordinate part; the essential element in determining the cost and the reliability of electric power is the prime mover; that is, the intermediary step between nature's stores of energy and the dynamo shaft.

The cost of electric power consists of three parts.

A. The fixed cost or permanent cost; that is, the cost depending on the size of the station, but not on the amount of power supplied by it.

B. The proportionate cost; that is, cost proportional to the amount of power delivered.

C. The reliability insurance; that is, the additional cost required to assure the desired reliability or continuity of service.

A. FIXED COST

1. *Interest on the investment in the plant*. This factor varies very greatly with the form of the available energy. It is frequently

very large with water-power, owing to the hydraulic development required—dams, pipe-lines, land to be flooded for water storage, power stations and prime movers, transmission lines, etc.

It also depends on the prevailing rate of interest and on local conditions: whether a market is waiting for the power and capital for the development is easily obtained; whether a market is within reach and can be developed; or whether a market has first to be created.

2. *Depreciation of the plant.* This factor is different for different parts of the plant. For instance it is very low for buildings and for line copper; it is high for apparatus such as railway motors, which by the nature of their service operate on a narrow margin.

In considering depreciation, the " useful life " of the apparatus must be recognized. It may often be much shorter than the total life. The ratio of the useful life to the total life varies with different apparatus. Electrical machines and prime movers and other parts of the plant, for instance, may still be in condition to give many years' service, but nevertheless their further use is uneconomical, and their useful life is thus ended. This condition may be due to the advance of the art, which makes other types of apparatus so much more economical that the cost of the difference in economy properly capitalized exceeds the cost of reconstruction of the plant. It may be due to the fact that with the increase of the market the size of units initially chosen may have become too small, or the space-economy too low, or the voltage too low for economy. Furthermore, the cost of attendance or of maintenance may be so much lower with the more modern apparatus as to make it uneconomical to retain the existing plant.

Just as it was realized many years ago that with the incandescent lamp there was a difference between the total life and the useful life, that after a definite period it did not pay to maintain incandescent lamps in service, even if still operative, so with all engineering apparatus a similar " smashing point " exists, a point where economy requires renewal of the plant, even if still operative. At this point the useful life of the old plant is ended; it should be thrown out with whatever salvage is feasible—either by use as reserve plant, or to take care of peak loads, or to be operated elsewhere when space economy limited the useful life. In considering depreciation, the useful life of the apparatus should thus be considered.

3. That *part of the operating expense* which does not depend on the use of the plant, as superintendence, some supervision, etc., such repairs as maintenance of dams and hydraulic development, etc.

B. Proportionate Cost

1. This comprises the *cost of energy* and *accessories* to its conversion—fuel, condensing water and lubricating oil in thermodynamic engines, water (where a charge is made for the water power) and oil in hydraulic plants, etc.

2. *Labor and attendance*, including that part of supervision which varies with the power utilized.

3. *Maintenance, repair and depreciation* of the plant, as far as they depend on the use of the apparatus; for instance, brush renewals, commutator repairs, railway motor depreciation, etc.

C. Reliability Insurance

1. This comprises the *overload capacity* of apparatus in power, voltage etc., provided to take care of emergencies.

2. *Duplication of parts* of the plant, as reserve units, duplication of exciter plant, of lines, and feeders, etc.

3. *Additional plant*, as steam reserve with water-power plants, storage-battery reserve, tie lines with other systems, etc.

Some of the items of the cost may belong partly in one, partly in the other class; depending on local conditions, it may properly be chargeable to either one or another subdivision. For instance, the cost of developing water storage would belong under *A*, if the power capacity of the plant depends on it, while it would be chargeable to reliability insurance *C*, if provided to guard against failure of the power in unusually dry seasons.

The relative weights of *A* and *B* depend largely on the *load-factor*; that is, the ratio of the average to the maximum power. With a poor load-factor. item *A* is far more important. It recedes in importance with the improvement in the load-factor.

Attention is drawn to the recognition of Class *C*, the reliability insurance, as a distinct and essential part of the cost of power, separate from *A* and *B*. Item *C* again consists in part of the character of fixed cost, and in part of the character of proportionate cost. Nowadays, when the lay public is interested in the cost of electric power, and is comparing plants which may be very different in regard to reliability of service (as supply from a water-power over a single transmission line without steam reserve compared with a city steam station with storage-battery reserve), it appears desirable to recognize the insurance of continuity of service as a separate part of the cost of electric power.

The great difficulty met with in discussing reliability of service is the absence of an established standard; for what one engineer may consider as perfectly satisfactory service, may be considered as entirely unsatisfactory by another engineer.

A classification of electric power supply regarding its reliability may be made by the number of shutdowns per year. Four classes of shutdowns may be distinguished, by the time of their duration:

a. Less than one second; that is, less than the time which would throw synchronous apparatus out of step. A few seconds' failure of power in the supply of a synchronous motor or converter means re-starting and synchronizing, and thus for the power users depending on the synchronous machine represents a very much longer shutdown.

b. Less than 20 minutes; that is, the time in which synchronous apparatus in a well organized plant can be put back into service. In lighting circuits, while the failure of the lights is annoying, it is not usually serious, and the loss of time by failure of the power supply is moderate.

c. Less than three hours; that is, the time sufficient to start anew a steam plant, replace or repair damaged apparatus as transformers, repair lines, etc., and a time which, if the shutdown occurs only rarely, in general does not warrant the installation of a separate system of light and power supply, as gas or a private steam plant.

d. More than three hours. This represents a complete breakdown of the system. If this is likely to occur, it requires the provision of private lighting or power-plant service wherever power is used from the electric supply system.

In estimating the reliability of service the shutdown of a part of the system would be considered as a part of a shutdown, in proportion to the connected load. Thus a shutdown of a section comprising $1/n$ of the total connected load of the system would count as $1/n$ of a shutdown. This method of counting gives the average number of shutdowns per customer.

Voltage variation beyond the limits permissible in good service—about 2% in lighting, and 10% in power supply—would be considered as a partial shutdown, about in the following manner:

A voltage variation of 2 per cent to 10 per cent as one-tenth of a shutdown in a lighting system, but does not count in a power-supply system.

A voltage variation of 10 per cent to 50 per cent as one-half of a shutdown.

A voltage variation of over 50 per cent counts as a complete shutdown.

It appears reasonable to omit from consideration any shutdown made for purposes of change, repair, etc., provided the users have been notified beforehand.

By the yearly number of shutdowns, an electric power supply would be classified as:

1. First-class service:

$a < 4$ per year; $b < 1$ per year; c and d absent.

2. Good service:

$a < 12$ per year; $b < 4$ per year; $c < 1$ per year; d absent.

3. Second-class service:

$a < 52$ per year; $b < 12$ per year; $c < 4$ per year; $d < 1$ per year.

4. Third-class service:

$b < 52$ per year; $c < 12$ per year; $d < 4$ per year.

5. Unsatisfactory service, suitable only as auxiliary power, etc.

Some such schedule of classes of service appears urgently needed, to give a meaning to statements and discussions on character and reliability of service.

The above proposition is probably the best that can be expected at present, without putting too large a majority of the electric systems into the second and third classes. It must be realized, however, that the standard set by it is far lower than that maintained in most gas or water-supply systems, that what is here called good electric service would be entirely unsatisfactory in a gas service. However, this lower standard is permissible, owing to the far greater safety of electric power, in which a temporary interruption of the supply is not liable to such disastrous results as would be the case with gas service.

II.

In discussing the features of prime movers it is necessary to distinguish between those which are inherent in the type of apparatus—as the dependence on meteorological conditions in the hydraulic plant, the high temperature in the gas engine—and those which are incidental. The incidental features are due to the particular form of design, and therefore defects from this cause are usually temporary. While a defect in the prime mover may be just as serious to the operation of the plant, even if not inherent in the type of apparatus, in a comparative discussion such features cannot be given the same weight, as they are not permanent. They are eliminated with the advance of the art, or avoided when recognized; as, for instance, the difficulties found with the convection of superheated steam, due to the considerable expansion and contraction of piping caused by the high temperature differences.

Most of the features of prime movers pertain either to economy or to reliability.

A. ECONOMY

1. *Power economy or efficiency.* With a thermodynamic engine the total efficiency is the product of mechanical efficiency, thermodynamic efficiency, and producer efficiency. The thermodynamic efficiency is the ratio of the available energy in the engine to the total heat energy supplied to it. The mechanical efficiency is the ratio of the mechanical output at the engine shaft to the available energy in the engine. The producer efficiency is the ratio of the total energy of combustion of the fuel to the heat energy supplied to the engine; it thus comprises furnace efficiency, boiler efficiency, superheater efficiency in a steam engine, or producer efficiency in a gas-producer plant, etc.

The thermodynamic efficiency depends essentially on the temperature range utilized by the engine, and to a lesser extent on the thermodynamic cycle used by it. It increases with increase of the temperature range.

The mechanical efficiency depends on the cylinder volume per kilowatt output, on the temperature range, the pressure and the pressure differences, the momentum of the moving parts, their velocity and the nature of the velocity, whether reciprocating or rotating, etc. In general it decreases with increasing size and mass per kilowatt, with increasing speed, (especially when reciprocating) and with increasing temperature and pressure differences. It thereby depends largely on the available energy per unit volume and per unit weight of the working fluid.

Consideration of the producer efficiency opens such a wide field as to be beyond the scope of this paper.

As the cost of the energy is only a part of the proportionate cost of power, the importance of the efficiency varies with the proportion which this part of the cost bears to the total cost.

Efficiency thus depends upon numerous considerations—the size of plant, load-factor, etc. In general, high engine efficiency increases in importance with increasing size of plant, and with increasing load-factor, and in such plants becomes the most important factor. In small plants with a poor load-factor it may drop into secondary rank, compared with the fixed cost A, and the cost of maintenance and repair, especially if in the design of the plant the mistake is made of giving too much attention to high efficiency, and thereby too little to reliability and low maintenance.

2. *Space economy.* This factor depends essentially on the engineering skill and judgment in the design of the plant, and on the type of the prime mover. It affects the fixed cost of power, and varies greatly in importance; for instance, space economy in the huge plants of our large cities is of very great importance, while for smaller country plants, or plants in locations where unlimited space is available, it becomes of very little importance.

3. *Investment economy.* This depends largely on the available market, and the desired quality of the power. It affects the choice of the prime mover. With an assured market, requiring a high grade of service, the large investment of a first-class modern plant with the best type of prime movers and ample reserve is most economical, while in many of the earlier railway plants the conditions were such that single-cylinder, non-condensing engines of the cheapest type gave the most economical and occasionally the only feasible arrangement. But even in the large first-class plants, in those parts of the plant that are only occasionally called upon for service, that is, which have a very low load-factor, good judgment may suggest a cheaper and correspondingly less efficient type of apparatus than would be economical in the engines which are continuously in service. Such a reserve and emergency plant thus offers a means of utilizing machinery which in the main plant has finished its useful life. To some extent this applies to the thermodynamic reserve of a water-power plant, especially where it is only rarely called into service, and economy in first cost and in space and simplicity may far outweigh high efficiency.

4. *Labor economy, as determined by the amount and character of attendance required.* With a high price and poor quality of skilled labor, prime movers which require a higher grade of attendance become less economical than less efficient prime

movers which can be operated by unskilled labor, or require only very little skilled labor, and especially in our country, the reduction of the amount of high-grade skilled labor is economically necessary. It is this feature which has forced the designers of prime movers and electrical apparatus to devote their attention chiefly to make the apparatus as "fool-proof" as possible, even if efficiency and other characteristics have to be sacrificed to some extent. This fact has to a considerable extent determined the trend of development of the industry, so that types of apparatus which have proved entirely satisfactory in other countries were a failure here, until they had been re-designed to meet the requirements of being operated by the available class of labor. A characteristic instance of the effect of price and character of labor is the general introduction of the enclosed arc lamp in this country, while abroad the open arc is universally used and the enclosed arc has never been accepted, due to its lower efficiency. As a result, the experience gained abroad with different types of prime movers and other apparatus is not directly applicable in our country, and conversely.

5. *Maintenance, repair, and depreciation.* This depends largely upon the type of prime mover, and in thermodynamic engines on the cycle used in the engine. Higher temperature differences, greater cylinder volume and piston pressure, heavier moving (especially reciprocating) masses, higher speeds (especially of reciprocating masses)—in short, greater mechanical and temperature stresses in general, other things being equal, tend to greater maintenance and repair cost and more rapid depreciation. Thus this item is to some extent proportional to the mechanical efficiency, and inversely proportional to the thermodynamic efficiency of the engine cycle.

The economic item of depreciation depends, however, not only on the wear of the apparatus, but also on the limitation of its useful life. In this respect it must be kept in view that with apparatus which is in a state of rapid development, as the steam turbine or the gas engine, the useful life should be expected to be shorter than with apparatus in a field in which no great development occurs. With a rapid advance in the development the time soon arrives where older apparatus is so far left behind as to make it more economical to replace it. This has been well illustrated by the history of the electrical industry. It would be an argument against the use of newer types of apparatus, and thus antagonistic to progress, if it were not for the fact that in the types of apparatus with which the new development competes, the useful life is shortened in the same or probably still greater degree, as either an extra rapid advance in their design must occur to meet the competition, or they would be replaced by newer types. Thus the useful life of the steam turbine, due to its rapid advance, must necessarily be shorter than the life of the steam engine would be if there were no steam turbine or gas engine; but owing to the existence of steam turbines and gas engines, the useful life of the steam engine, as limited by the advance of the art, is correspondingly shortened, as it faces displacement by steam turbine or gas engine or also has to advance more rapidly.

It will be seen, therefore, that in the economic characteristics of thermodynamic prime movers in general, efficiency and the other features are to some extent mutually conflicting. Engineering judgment must therefore decide on the relative weights of the different economic factors which enter into the choice of the prime mover in the individual case under consideration.

B. Reliability

Features, which are of importance for the reliability, that is, continuity of service, are:

1. The absence or presence of external influences beyond the control of the operating force, as meteorological effects, etc.

2. The design of the plant. This is an engineering problem outside of the scope of this paper. It is obvious, however, that an error in the design can rarely be remedied afterwards; therefore, before the plant is constructed and before the buildings are designed, the arrangement of prime movers and electrical apparatus should be designed to afford the greatest safety of operation. Frequently this has not been done. For instance, the architect of the buildings has overlooked the fact that the switchboards and controlling devices of our modern large, high-voltage electric plants require considerable space, and such apparatus—on which the safety of the system depends—has been crowded together in an altogether insufficient space, to the great detriment of the reliability of operation of the system. A marked improvement has taken place in this direction in the last few years.

3. The probable frequency of shutdown of the prime mover, and the liability of involving other machines by it, and the number of other units and reserve plant available. To some

extent this depends on the mechanical and temperature stresses in the prime mover; it is related to the economic item of maintenance, repair, and depreciation.

4. Rapidity of starting of apparatus, and getting them into service, to cope with such emergencies as a shutdown of the system or a part of it, as a breakdown of a transmission line or feeder, an accident to one or several units, etc., or even an unexpectedly rapid increase of load. Rapidity of reaction to changes of load; that is, speed regulation and voltage regulation, etc. These are important features in their effect on the reliability of service. They depend to a considerable extent on the type of prime movers and other apparatus, but to a still greater extent on the preparedness for such emergencies, and the organization of the operating force for it.

III.

The suitability of the different types of prime mover for the various economic and other requirements of electric service, as discussed above, are best seen by considering their characteristic features.

The available types of prime mover are:

A. The hydraulic turbine. The impulse type, the reaction type, and their various combinations.

B. The steam engine. Condensing and non-condensing, with and without superheat.

The steam turbine. Condensing and non-condensing, with and without superheat.

The gas engine. Using the available fuel directly, as natural gas, blast furnace gas or liquid fuel, and

The gas engine. With producer plant converting solid fuel into gas.

The gas turbine does not yet exist, but as it undoubtedly will arrive sometime, some consideration is given to it in the following.

A. HYDRAULIC PRIME MOVERS.

The most prominent characteristic of hydraulic power is its dependence on meteorological conditions, dry seasons, freshets, ice in the water supply; and mechanical and electrical interference with the transmission lines connecting the power with its market. As a result the reliability of hydraulic power is inherently far below that of steam power. To give the same class of electric service, therefore, the reliability charge, in the form of duplication of plant, of steam reserve, etc., is far higher than with a steam plant close to its market. In this respect climatic conditions naturally exert a great effect.

The fixed cost is usually very high, due to the expensive hydraulic development required. It is especially high if water storage has to be provided; but this also depends largely on the local conditions of the water-power.

The proportionate cost, is, however, very low, owing to the absence of cost of fuel. This is the redeeming feature of the hydraulic plant, which gives it an advantage over steam power. Nevertheless, even with an extremely low proportionate cost, the high fixed cost and the high cost of reliability insurance greatly reduce the difference in the cost of steam power and of water-power of the same quality. Under very unfavorable conditions, it may even make the water-power more expensive than the steam power.

Owing to the high fixed cost and low proportionate cost, water-power depends on a good load-factor still more than does steam power, to such an extent that it may occasionally be economical to oversell the water-power, thereby keep constant load on it, and take care of peak loads, etc., by auxiliary steam plant.

B. THERMODYNAMIC PRIME MOVERS.

The thermodynamic efficiency is essentially a function of the temperature difference, on which the engine operates. The mechanical efficiency, maintenance cost, and reliability depend largely on the mechanical and temperature stresses in the prime movers, the available energy per unit weight and unit volume of the working fluid—steam or air—and on the speed of the engine.

To compare the different types of prime movers in this respect to determine how far certain features, as high mechanical stresses, low space economy, high thermodynamic efficiency, etc., are inherent in the type of prime mover, requires a study of their thermodynamic cycles.

In Fig. 1 is plotted, with the temperature in degrees centigrade as abscissas, the available energy in kilojoules per kilogram of the working medium: steam or air, for the three typical air cycles, and for steam used non-condensing and condensing, in the latter case with a condenser pressure $p = 0.1$ kg. per cm^2, or about 27 in. vacuum; that is, about the average between that of the steam turbine and that of the reciprocating engine. The corresponding pressures are shown in dotted lines, and the thermodynamic efficiencies in the upper part of Fig. 1. Figs. 2 to 6 give some typical cycles, and Tables I and II the constants of these cycles.*

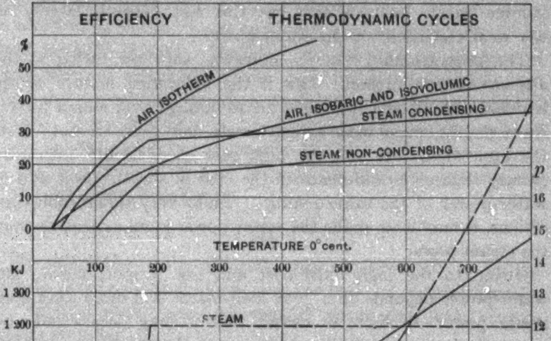

FIG. 1

A pressure limit of $p = 12$ kg. per cm² (about 170 lb. per sq. in.) is assumed for steam, while for the air cycles a maximum of twice this pressure has been allowed.

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* Obviously, these curves and tables are approximate only, as thermodynamic calculations do not allow of the same exactness as electric engineering calculations, since some of the essential constants, as the specific heat, the adiabatic constant, etc., are not yet known with the exactness familiar in electrical determinations.

As will be seen in Fig. 1, the isothermic or Carnot cycle—that is, constant temperature admission, adiabatic expansion, constant temperature exhaust, adiabatic compression—does not give any appreciable output, nor can it use considerable temperature differences without going to impracticable pressures. Thus its existence is limited to the text books of thermodynamics. With a maximum pressure $p = 24$, the maximum energy available for the Carnot cycle is 78 kilojoules per kilogram of air, or about one-tenth of the available energy of saturated steam at half this pressure, and occurs at the relatively low upper temperature of 225° cent. This cycle is shown in Fig. 2, and is the " fattest "

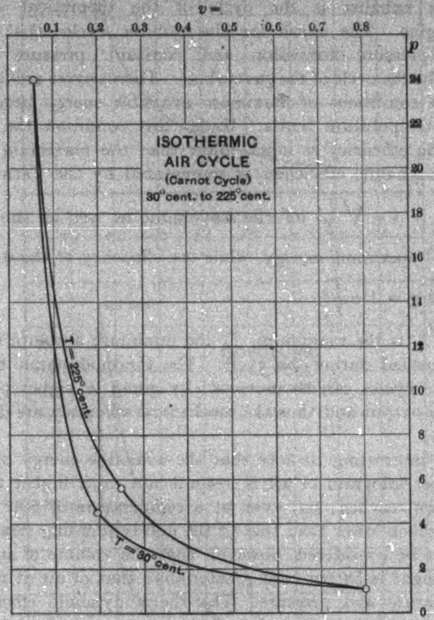

FIG. 2

Carnot cycle which can exist within the pressure limit of 24 kg. per cm^2. At higher temperatures the efficiency of the Carnot cycle increases, but the output decreases; the output vanishes, by the cycle collapsing into a line, at about 455° cent., or at a temperature far below that permissible in gas engines.

The curve for the isovolumic air cycle—that is, constant volume admission (constant volume combustion) and constant volume exhaust is the cycle of the theoretical or ideal gas engine. The curve for the isobaric cycle—that is, constant pressure admission and constant pressure exhaust would be the cycle of the gas turbine. These curves are calculated for the conditions of maximum available energy between the given temperature limits. Under this condition the thermodynamic efficiency is much lower than the maximum possible thermodynamic efficiency as represented by the Carnot cycle. It is: $\eta = 1 - \sqrt{\frac{T_2}{T_1}}$ for the isovolumic as well as the isobaric cycle of maximum energy, while the efficiency of the isothermic cycle is $\eta = 1 - \frac{T_2}{T_1}$,

where T_1 is the maximum, T_2 the minimum absolute temperature reached during the cycle. The thermodynamic efficiency of these cycles can be increased by going to higher pressures, but the output and thus the mechanical efficiency are decreased thereby.

It is interesting to note that the available energy of the air cycle per kilogram of air is insignificant until higher temperatures are reached; but even at a temperature of 800° cent. it is still much lower than that of the non-condensing steam cycle. It must be considered, however, that the volume of steam per unit weight is 58 per cent greater than that of air at the same temperature and pressure. The thermodynamic efficiency of these cycles is less than that of the steam cycle for lower temperature, but rises far above it at higher temperatures.

The relatively low pressure is interesting. This pressure gives the maximum output in an isobaric air cycle, and shows that the development of the gas turbine will take place at relatively moderate pressures.

In Figs. 3 and 4 are shown the isovolumic and isobaric cycles for 800° cent. maximum temperature and the same conditions of maximum available energy as in Fig. 1. Obviously, the high-pressure peak at the beginning of the expansion, in Fig. 3, is cut off by delayed combustion, etc. Even at the highest temperature the maximum output pressure of the isovolumic cycle does not reach that occurring in the Carnot cycle at an insignificant output.

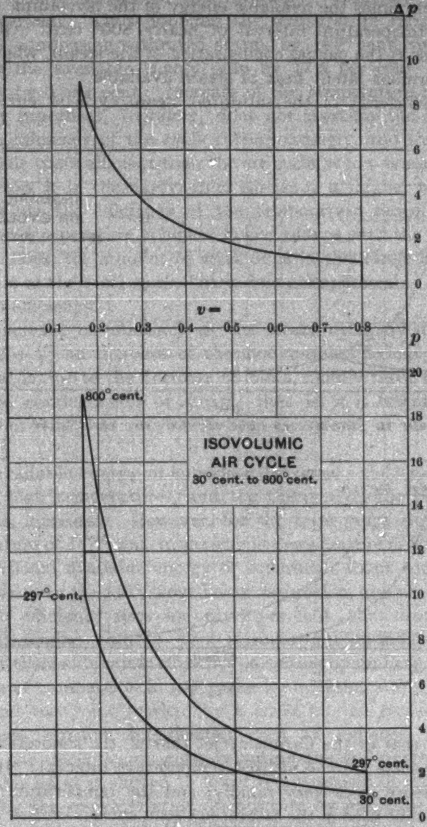

Fig. 3

The steam curves in Fig. 1 are interesting from the very rapid rise and very high values of available energy. Thus in the temperature interval of 141° cent., between boiler and condenser temperature, the steam cycle gives per kilogram more than four times the available energy of the isovolumic air cycle in the temperature interval of nearly 800° cent. Obviously, the cause is the partial condensation of the steam, which makes the enormous latent heat of steam available.

The efficiency of the saturated steam cycle is virtually the same as that of the Carnot cycle; that is, the theoretical maximum possible for the utilized temperature interval. However, the pressure rises very rapidly, and the temperature interval which can be used in the saturated steam cycle is limited thereby. Hence from the temperature of 187° cent., corresponding to the steam pressure of $p = 12$, the further increase of temperature occurs not at saturation and with rising steam pressure, but at constant steam pressure, by superheat.

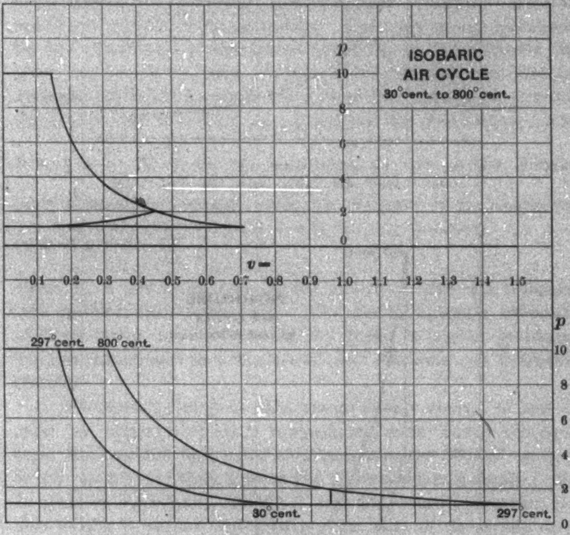

FIG. 4

These curves of superheated steam* show the small increase of available energy of superheat, until very high superheats, gas-engine temperatures, are reached. They show especially the very small increase of thermodynamic efficiency resulting from superheat. Thus doubling the temperature range (141° cent.), of condensing saturated steam, by 141° cent. superheat increases the available energy only by 17.5 per cent, and the efficiency by 1 per cent. Increase of the temperature range of steam by superheat, therefore, does not increase the thermodynamic efficiency of the cycle correspondingly, and the steam cycle, while more efficient than the air cycle at low temperature, drops below it in thermodynamic efficiency at higher temperature. While the efficiency of the temperature range beyond saturation temperature is higher in accordance with the thermodynamic laws, the amount of work done in this range is such a small part of the total work that it does not appreciably increase the total efficiency.

The increase of efficiency of the steam cycle by superheat is not due to an increase of thermodynamic efficiency of the cycle, but is due to the decrease of losses, mainly those resulting from the condensation of steam; that is, it is essentially an increase of what has previously been considered as mechanical efficiency.

The available energy of superheat becomes considerable only at very high temperatures, and the thermodynamic efficiency, therefore, increases. However, for the total range from boiler temperature of 187° cent. to gas-engine temperature of 800° cent., the additional available energy of superheat about equals that of the steam in the 141° range below saturation, and the thermodynamic efficiency rises by only 9 per cent., thus dropping far below gas-engine values. This is important as indicating the losses of thermodynamic efficiency, resulting by limiting the temperature of combustion in gas cycles by injecting water.

Beyond the point marked by a circle on the steam curves, the steam remains superheated even at exhaust pressure; that is, the cycle occurs entirely within the gas range. Obviously, this point is shifted to lower temperatures in the turbine engine by the re-evaporation of moisture by mechanical losses.

It is interesting to note the large amount of available energy of steam below atmospheric pressure, 350 kilojoules per kilogram of steam, which is used in the low-pressure steam turbine.

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* Calculated with the specific heat $c_p = 0.525$ at $p = 12.$ and the adiabatic constant $a = 1.286$.

Fig. 5 gives the cycle of non-condensing saturated steam, and Fig. 6 the turbine cycle of condensing saturated steam.

Comparing Figs. 4 and 5 the greater width of the area of the steam cycle is illustrated. In Figs. 3, 4, and 5 the cycle is shown in the upper part of the figure, modified by subtracting the compression curve from the expansion curve, as this gives the area, and thereby the available energy, in a form more convenient for comparison.

Characteristic of all thermodynamic cycles, Figs. 4, 5, 6, is the very large volume at the end of the expansion; that is, the area runs out in a long and low triangular shape. To carry the adiabatic expansion down to exhaust pressure, therefore, would require abnormally large cylinder volumes in a reciprocating engine, and correspondingly larger mechanical losses; therefore the expansion has to be broken off long before exhaust pressure is reached, about as indicated in the curves, or even at still higher pressures. As a result the reciprocating engine cannot get the full benefit of very low condenser pres-

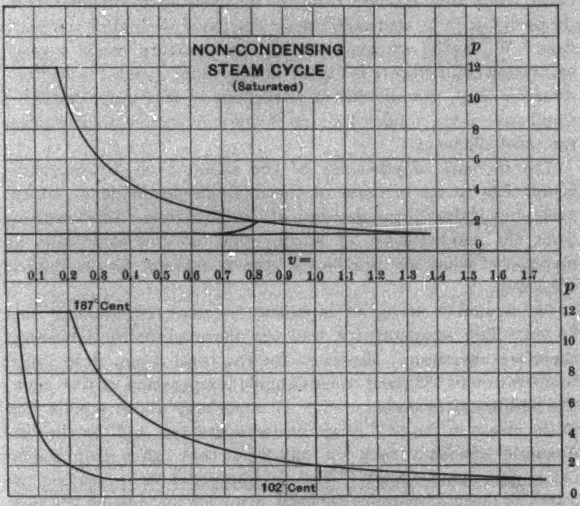

FIG. 5

sures, while the turbine engine is not limited in this respect. For instance, between $p = 0.07$, or 28 in. vacuum, and $p = 0.2$, as the pressure at the end of the expansion of a reciprocating engine, the available energy per kilogram of steam is 153 kilojoules, or about 37 per cent of the total energy of the non-condensing steam cycle. Of this only 100 kilojoules, or about two-thirds is used is the steam engine, while the total is used in the turbine. Hence the steam turbine gains far more by high condenser vacuum than does the reciprocating engine. With a steam turbine of condenser pressure $p = 0.07$ (28 in. vacuum) the available energy of the steam would be higher by 42 kilojoules, than the steam curve in Fig. 1.

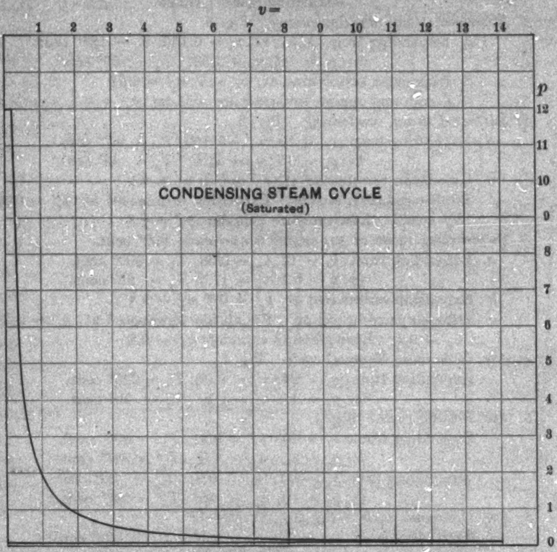

FIG. 6

To show the relative magnitude of the quantities, the results of six typical cycles are calculated in Tables I and II.

As seen from Table II, the available energy E per kilogram of working medium is highest for steam with condensation, lowest for the Carnot cycle of air. The weight w of steam or air required per 1000 kilojoules of available energy, is given in column 6, and varies between 0.68 kilogram for steam superheated to 800° cent., and 12.8 kg. for the Carnot cycle. Column 7 shows the maximum volume v_0, per 1000 kilojoules, assumed by the working medium at the end of the expansion. Here 2*a*, 3*a*, and 4 are such as to show the impracticability of these cycles for an engine

TABLE I.

Thermodynamic Cycles

1. *Saturated steam, non-condensing.* Fig. 5.
  a. Expanding from: $p_1 = 12$; $v_1 = 0.166$; $T_1 = 187^\circ$ cent.
  to: $p_2 = 1.1$; $v_2 = 1.38$; $T_2 = 102^\circ$ cent.
  b. Expansion terminated at: $p_1' = 2$; $v_2' = 0.81$
  c. Compound engine, low-pressure cylinder: $p_1' = 3.5$; $p_2 = 1.1$
2. *Saturated steam, condensing.* Fig. 6.
  a. Expanding from: $p_1 = 12$; $v_1 = 0.166$; $T_1 = 187^\circ$ cent.
  to: $p_2 = 0.1$; $v_2 = 11.5$; $T_2 = 46^\circ$ cent.
  b. Expansion terminated at: $p_2' = 0.2$; $v_2' = 6.2$
  c. Triple-expansion engine. Expansion terminated at: $p_2' = 0.2$; $v_2' = 6.2$. Low-pressure cylinder: $p_1' = 0.8$.
3. *Superheated steam of gas-engine temperature,* 800° cent.
  a. Expanding from: $p_1 = 12$; $v_1 = 0.38$; $T_1 = 800^\circ$ cent.
  to: $p_2 = 0.1$; $v_2 = 17.5$; $T_2 = 98^\circ$ cent.
  b. Expansion terminated at; $p_2' = 0.2$; $v_2' = 9.4$
  c. Triple-expansion engine. Expansion terminated at: $p_2' = 0.2$; $v_2' = 9.4$. Low-pressure cylinder: $p_1' = 0.8$.
4. *Air, isothermic, (Carnot) cycle.* Fig. 2.
  Expanding from: $p_1 = 24$; $v_1 = 0.06$; $T_1 = 225^\circ$ cent.
  to: $p_2 = 1.1$; $v_2 = 0.8$; $T_2 = 30^\circ$ cent.
5. *Air, isobaric cycle.* Fig. 4.
  Expanding from: $p_1 = 10$; $v_1' = 0.31$; $T_1 = 800^\circ$ cent.
  to: $p_2 = 1.1$; $v_2 = 1.5$; $T_2' = 297^\circ$ cent.
  Compressing from $p_2 = 1.1$; $v_2' = 0.8$; $T_2 = 30^\circ$ cent.
  to: $p_1 = 10$; $v_1 = .166$; $T_1' = 297^\circ$ cent.
6. *Air, isovolumic cycle.* Fig. 3.
  Expanding from: $p_1 = 19$; $v_1 = 0.166$; $T_1 = 800^\circ$ cent.
  to: $p_2' = 2.1$; $v_2 = 0.8$; $T_2' = 297^\circ$ cent.
  Compressing from: $p_2 = 1.1$; $v_2 = 0.8$; $T_2 = 30^\circ$ cent.
  to: $p_1' = 10$; $v_1 = 0.166$; $T_1' = 297^\circ$ cent.

in which the maximum volume is of importance; that is, a cylinder engine. Cycles 2*a* and 3*a* thus are turbine cycles.

At the same piston speed, that is, the same number of revolutions and same piston stroke, the product of maximum pressure (column 4) and maximum volume (column 7) is proportional to the piston pressure, and these relative piston pressures: $P = p\, v_0$, are given in column 8. This column is an indication

1	2	3	4	5
Available energy per kg.	Thermodynamic efficiency	Maximum		
K J	%	Temperature ° cent.	Pressure kg per cm²	Volume m³ per kg.
E	*η*	*T*	*p*	*V*
		1. Non condensing saturated steam.		
		a. Turbine cycle.		
416	17.4	187	12	1.38
		b. Engine cycle.		
395		187	12	.81
		c. Low pressure cylinder of compound engine.		
416		138	3.5	1.38
		2. Condensing saturated steam.		
		a. Turbine cycle.		
734	27.8	187	12	11.5
		b. Engine cycle.		
715		187	12	6.2
		c. Low pressure cylinder of triple expansion engine.		
715		93	0.8	6.2
		3. Condensing steam superheated to gas engine temperature (800° cent.)		
		a. Turbine cycle.		
1480	37.0	800	12	17.5
		b. Engine cycle.		
1460		800	12	9.4
		c. Low-pressure cylinder of triple expansion engine.		
1460		300	0.8	9.4
		4. Isothermic air cycle. (Carnot cycle.)		
78	37	225	24	0.8
		5. Isobaric air cycle. (Turbine cycle.)		
240	47	800	10	1.5
		6. Isovolumic air cycle. (Engine cycle.)		
172	47	800	19	0.8

In a turbine engine, at 135 metre-seconds wheel-speed,
wheel) would in the condensing steam turbine of exhaust
sion and exhaust pressure, in the reciprocating engine 2*d*, the
1000 kw. output.

In a gas turbine, 5, the maximum outflow section under
cu. ft. cylinder volume in 6, per 1000 kw. output.

I. (Steinmetz)

Thermodynamic Cycles.

7	8	9	10	11	12
kilojoules energy	Relative piston pressure $P = p v_0$	Per 1000 kw. output, at 60% resp. 50% mechanical efficiency, 60% boiler and furnace efficiency, double-acting engine 75 rev. per min.			
Max. Volume m³		Cylinder Volume		kg. per kw. hour, steam or air	Total Efficiency
		m³	cu. ft.		
v_0		V		W	
3.33	39.8	2.21	78	14.4	6.3
2.05	24.6	1.37	48	15.2	6.1
3.[illegible]	11.6	2.21	78	14.4	6.3
15.7	188	10.5	370	8.0	10.0
8.7	104	5.8	205	8.4	9.8
8.7	7.0	5.8	205	8.4	9.8
11.[illegible]	142	7.9	280	4.1	13.3
6.[illegible]	77	4.3	152	4.2	13.1
6.[illegible]	5.1	4.3	152	4.2	13.1
10.[illegible]	247	8.2	290	92	18.5 (14)
6.[illegible]	62.5	5.0	176	30	23.5 (17.6)
4.[illegible]	84	3.7	130	42	23.5 (17.6)

ection of the steam passages, (at the exit side of the last low-pressure be only 1400 cm³, or 1.5 sq. ft., while under the same conditions of admis- is 370 cu. ft., and in 2b, at $p = 0.2$ exhaust pressure, still 205 cu. ft. per

ditions would be only 660 cm³, or less than 0.75 sq. ft., compared with 130

of the mechanical strains which have to be taken care of in the engine design.

Column 8 shows the impracticability of utilizing the full pressure range of a condensing steam engine in a single cylinder—even if it were otherwise permissible—due to the excessive piston pressure resulting in this case; it also shows the enormous reduction of piston pressure by subdivision of the expansion, from 24.6 to 11.6 in the compound non-condensing engine, and from 104 to 7.0 in the triple-expansion condensing engine with saturated steam. Very striking, however, are the much higher piston pressures of the air cycle; that is, the gas engine: 84 in the isobaric and 62.5 in the isovolumic cycles, compared with 7 in the condensing triple-expansion steam engine. While by different assumptions, regarding pressure, temperature, etc., the numerical values may be somewhat varied, the differences between the two types of engine are of such magnitude as to exhibit a characteristic or inherent feature of the cycles.

In the last four columns are given, for 1000 kw. output, the values of cylinder volume in m^3 and cu. ft., of kilograms of steam or air consumed per kilowatt-hour, and the total efficiency, under the assumption of 60 per cent mechanical efficiency of the steam cycle and 50 per cent mechanical efficiency of the air cycle*, for a double-acting engine of 75 rev. per min., under the assumption of 60 per cent boiler and furnace efficiency; that is, ratio of heat units supplied to the engine to heat units representing the chemical energy of the fuel. The efficiencies of the air cycles are given for 100 per cent producer efficiency; that is, the case of gaseous or liquid fuel. In brackets are added the efficiencies for a plant making its gas from coal, by assuming 75 per cent producer efficiency.

Table II shows the characteristic and inherent differences between steam engine, steam turbine, and gas engine. The steam turbine can utilize the expansion as far down in pressure as condenser design permits, and is of smaller size than the steam engine, owing to the higher velocities permissible by the rotary motion.

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* By mechanical efficiency is understood the ratio of mechanical output to the available energy of the cycle. The mechanical efficiency thus includes all of the losses between the available energy and the indicated engine output, as condensation, radiation, delayed combustion, throttling, steam friction, etc., which are not included in the ratio of brake horse power to indicated horse power.

Characteristic of the gas engine, compared with the steam engine, are higher piston pressures; thus heavier reciprocating masses, and thereby heavier construction, larger sizes, and greater mechanical losses, and lower space economy, especially when compared with the steam turbine. From the higher mechanical stresses inherent to the gas engine must be expected a lower reliability of service, or a higher class of the required attendance, or a more difficult and expensive engine design. Also characteristic of the gas-engine cycle is a very much higher thermodynamic efficiency which, even when allowing for the lower mechanical efficiency resulting from the higher mechanical stresses, is still very far above that of the steam engine, especially when gaseous fuel is directly available, and no producer plant is required.

In general, however, in discussing gas engines, the two distinctly different cases must be separated:

a. Where gaseous or liquid fuel is available, as in the blast-furnace gas, natural gas, and the automobile engine.

b. Where gaseous fuel has to be produced from coal by a separate plant.

When balancing the advantages of higher efficiency against the disadvantages resulting from the higher mechanical stresses, the difference between the two cases may often be the determining feature in the choice of the prime mover for maximum total economy.

DISCUSSION ON "PRIME MOVERS." NEW YORK, FEBRUARY 19, 1909.

President Ferguson: This is a subject in which we all are vitally interested. There probably has been more done in the last five or six years in the development of prime movers than was accomplished in the previous 20 years. This serves to emphasize the importance of considering the question of depreciation in the broad way in which the author has approached it, and I wish to call attention to the happy manner in which he has expressed it. As an illustration of the truth of what he has said, I might cite something that may be of interest to you.

It is now six years since the largest steam-turbine powerhouse was completed in this country. There were at that time four turbines installed. Thirty days ago there was begun the dismantling of the first of these four turbines. That is a very short period of time in which to have had the turbine installation in use, but it bears out exactly what Dr. Steinmetz has said in his paper. The economy of the present turbine, compared with those which were installed six years ago, has so improved that it pays the company to scrap the turbines it put in at that time and install new ones of a more modern type; in other words, the saving to be effected, due to the increased economy of the new turbines, when capitalized, will more than pay for the cost of the new turbines. Not only has the economy of prime movers been improved, but their reliability as well, both contributing to place the producing and marketing of electricity and electrical apparatus on a more firmly established basis. This appeals, naturally, to those of us who are engaged in the operating department of engineering, carrying with it the great responsibilities not only to investors but to the general public, whose servants we really are, and we appreciate most highly the interesting and instructive manner in which the author has brought out the necessity for considering in all statements of cost the value of reliability.

Charles E. Lucke: It seems to me the first part of this paper is mainly a repetition of many elementary facts almost axiomatic, in which the only idea that strikes me as new is the proposition concerning reliability insurance. That seems worth while. As to the rest, I confess I am distinctly disappointed, especially in relation to the thermodynamic efficiency part. I have studied things of this sort a good many years, it is my own specialty, and it may be that I expect too much, but one fact I cannot overlook in this thermodynamic efficiency analysis is that thermodynamic efficiency, as it is taken up in the paper, referring only to the cycle, depends primarily on two things (*a*) the nature of the cycle, that is to say, the sort of phases and order of succession of the phases or processes, to use a better word, and (*b*) the extent to which each phase is carried.

The order in which the processes are carried out will affect the efficiency, in fact it will determine it, with one exception, and that exception is the equation of condition that fixes the extent of the phases. If it is desired to adiabatically compress or heat at constant volume, the nature of the process is defined, and that is the first step in fixing the possibility of the cycle, the next step being, how much heat is added or how much the gas is compressed. What fixes the thermodynamic efficiency of the cycle, as such, is just these things: the nature of the processes, the order of the succession, and the extent of the heating, the expansion, cooling or compression.

The author has assumed certain cycles, which are very well known, which have been studied repeatedly, and which are in nearly all the elementary books. The study of these cycles is proper subject matter for a third year course, such as we have at Columbia, or, in a not very advanced institution, for a fourth year course. The author has assumed certain limitations to the extent of certain phases by fixing pressures and temperatures, purely arbitrarily, and the results and conclusions are worth no more than the assumptions. Any other assumptions that any one else considers reasonable will bring other results, and we might have endless controversy concerning the conclusions. Every man's conclusions would be as good as the others so far as one set of assumptions is as reasonable as the other.

The author has fallen back in two or three places on that old statement in every text-book, which is generally misunderstood: "The thermodynamic efficiency is essentially a function of the temperature difference, on which the engine operates." This is a variation on the statement of the Carnot cycle law, which is ordinarily set down as follows: the maximum efficiency obtainable for a given temperature range, is fixed by a certain expression, usually $\frac{T_2 - T_1}{T_2}$. As a matter of fact the actual efficiency of any cycle has very little to do with this, has no more to do with it than my income has to do with the wealth of the nation, although the wealth of the nation certainly limits my income. It is quite true that Carnot's cycle yields an efficiency which is the highest possible for the temperature range, and it is likewise true that no gas cycle comes anywhere near the Carnot limit.

We are especially concerned with the gas cycle. The efficiency of any gas cycle is not a function of the temperature range, it is a function of, the nature of, the order of succession of, and the extent of each phase making up the cycle.

As engineers what do we care about the temperature range anyway? Do we approach the gas engine, the question which Dr. Steinmetz has finally interested himself in, by saying let us compress this gas to a certain pressure, and then have a constant volume rise to a temperature of 800 degrees cent. or

700 degrees cent., or 900 degrees cent.? We do nothing of the sort. We put into the gas mixture as much heat as we can, and do not care what the resulting temperature is. We put just as much heat into the gas as we can, to do as much work as possible in the cylinder, and the maximum temperature nobody knows the value of nor cares about. We do know how much work we can get, how much efficiency we can get, and also, that it has nothing to do with the temperature range.

It is possible, by taking proper assumptions for all variables, by setting up mathematical or other criteria by which to judge these results, for each man to arrive at results in his own particular way, and all different. If you will go through the literature on the subject you will find laws enough derived in this way to prove almost anything. Such cyclic analysis is almost as valuable as the Bible to prove things. An expression can be found to prove almost any statement, and another one to disprove it. Change the assumptions, always keeping them within the range of what you can induce some one to say is reasonable, and contradictory results can easily be obtained. I think as a consequence of this situation that this analysis of thermodynamic efficiency is not very valuable.

I have been carefully looking through the paper—for a conclusion. I have been trying to find out just what Dr. Steinmetz was trying to show, to throw, if possible, some light on the assumptions he uses, and I have not been able to find any conclusions. If the conclusion is that the gas engine cannot have as high an efficiency as the steam engine then the conclusion is absurd.

Henry E. Longwell: The opening sentences of Dr. Steinmetz's paper constitute a cheering message to those of us whose daily bread depends on the continuance of a demand for prime movers. When one who is not, and who cannot hope to be, versed in the intricacies of electrical science, hears and sees evidence of what he imagines to be mechanical work done by that phenomenon which we call lightning, he perhaps should not be too harshly criticized if he should have conceived the idea that electrical energy does exist in nature. It is not improbable that the school-books of our childhood days are largely responsible for the inculcation of this disquieting idea in the unsophisticated mind. By their persistence many of us have been led to unconsciously accept as classic, the crude experiments and deductions of that archaic philosopher and physicist, Benjamin Franklin.

During a life which is still a little inside the alloted span of three score and ten, I have seen so many impossible things happen, that for my own part, I am pretty well content to keep an open mind on all questions bearing on ultimate possibilities.

One can readily imagine a perfectly flat country, where the inhabitants could have no conception of hills and waterfalls. Such a country might be abundantly watered by lakes and canals, and yet one could forgive the wise men of this hypothetical nation if they asserted that water-power was not found in nature; that water-power could be available only through the kind offices of a prime mover that would convert the energy of fuel or of air currents into mechanical rotation or reciprocation, thus producing an artificial head or pressure that would enable the water to do work.

Considering the marvelous developments in electrical science during the lifetime of even the youngest member of this Institute, is it safe to set a limit to the possibilities of centuries yet to come? May it not be that we are now coming ourselves only with electricity as a *medium* for the transmission of energy? We can with certainty and precision produce by mechanical agencies, a difference of potential which enables this thing we call electricity to reproduce in a large measure the energy expended upon it. But does this fact make absolutely unthinkable the proposition that there may be natural differences of potential, yet undiscovered? However, with the authoritative assurance that we can never hope to eliminate that troublesome yoke-fellow of the electric generator, the prime mover, who alone prevents the business of operating an electric power plant from being a rapturous dream of profit and pleasure, we can, with all the more satisfaction and determination, apply ourselves with renewed vigor to the task of reforming him.

As regards the determination of costs of electric power, this is not essentially different from cost accounting in any other industrial enterprise. Industrial accounting is the most flexible and accommodating science known to mankind. Set half-a-dozen men to working independently on as many different sets of industrial cost records, and you will get just that number of different costs, and the correctness of each and every one is susceptible of proof by the unimpeachable rules of mathematics.

The total cost of electric power begins with the water on the hilltop, or the fuel in the earth, and ends only with the light emitted from the lamps and the power delivered from the shaft of the motor. A single individual or corporation rarely deals with the entire chain of operations, and the cost of the electric power, and the relative importance of the several items entering into the cost, depend largely on how many links in the chain are under consideration. For example, the author in speaking of the interest on the investment as a factor of the cost, says "It is frequently very large with water power, due to the hydraulic development required," etc. It might be added that it is sometimes very low, in cases where a hydraulic development company delivers water at the plant.

If we are to accept the author's inference that the cost of electric power stops at the terminals of the generator, and that the prime mover includes everything from the generator back to "nature's stores", then we must perforce agree with his statement that "In the cost of electric power the electric machine plays only a subordinate part; the essential element in determining the cost and the reliability of electric power is the prime mover."

There are some electric power enterprises that include expensive hydraulic development plants, or to speak more accurately, there are some large hydraulic development enterprises that include electric power plants as convenient transmitting mediums. I also know of one concern so happily situated as to be able to dispose of its output to a customer who furnished his own switchboard, transformers and transmission system. On the other hand, in how many instances does the owner or operator of an electric power plant get much nearer to "nature's stores" than the coal car on his railway siding, and in how many instances can he dispose of his output without delivering it on his customer's premises? Surely the instances are not so numerous as to warrant any such sweeping statement as that quoted.

I will not venture to intrude any discussion on the classification of electric power service into five different grades of quality. Your association may have under consideration the wisdom of setting up an official standard scale of badness. It might be useful to a manager of an electric power station as an instrument for convincing a complaining customer that he had no business to complain. To the manager whose plant is giving only mediocre service, it might be a comfort to know that he was still one or two degrees within the boundary of official recognition.

That part of the paper devoted to the thermodynamic consideration of heat motors, seems to be simply a brief resumé of several of the standard propositions that are demonstrated in most of the elementary text-books dealing with the subject. Those who have studied the mechanical theory of heat to the extent required in a modest technical course, will accept the statements put forth without argument. Those who have not a reasonable grounding in the subject must accept the statements as dogmatic.

We are introduced to a new unit of energy, which is referred to as the "kj." I am glad to be confirmed in my suspicion that this is a kilojoule, but it is a little difficult to see why it is used to the exclusion of the more conventional units that are commonly found in text-books on thermodynamics. As the value of a kilojoule differs from that of a British thermal unit by less than 6 per cent, we may accept it as a sort of "esperanto" term which conveys practically the same idea to those who think in metric measures and those who think in British measures. We also meet two old friends of the thermodynamic cycle family with new names. Isobaric and isovolumic would be convenient terms, were it not that the text-books recognize two other air engine cycles, those of the Ericsson and the Stirling engines, in which the isobaric and isovolumic features are respectively combined with isothermal expansion and compression, instead of adiabatic. I wonder if I dare suggest as a solution of the difficulty, isobarabatic and isovolumbatic—words which if not more significant, are more sonorous.

Referring to the efficiency curves in Fig. 1, we naturally expect the curve for the Carnot cycle to stand at the top, as it is our standard of the highest efficiency attainable. We expect the cycles which are designated as isobaric and isovolumic to fall short of the efficiency of the Carnot cycle, because they do not receive all their heat at the highest temperature, or reject all of it at the lowest. We expect the isobaric and isovolumic cycles to be equal in efficiency, for the reason that while they deal with different total quantities of heat, the amounts received and rejected at corresponding temperatures are strictly proportional. We expect the curve for saturated steam to coincide with the curve for the Carnot cycle between the same temperature limits, for the reason that the ideal cycle for saturated steam is a Carnot cycle. The only reason the curves do not coincide in the figure is, that different minimum temperature limits have been selected. We expect a decided change in the steam-cycle curve, at the point where superheat begins, for the reason that we there depart from the Carnot cycle and begin to take in heat at varying temperatures.

At higher temperatures we expect this superheated-steam curve to fall below the isobaric and isovolumic curves, for the reason that a larger proportion of the total heat dealt with was received at lower temperatures.

The curves of relative output per unit weight do not uncover any surprises. It is the heat and not the substance, that does the work. As steam has a greater heat-carrying capacity than air, naturally the work done by the heat that can be put into a unit weight of steam will be proportionately greater than that done by the smaller quantity of heat that can be put into a unit weight of air, temperature limits being the same.

The output of the isobaric cycle we expect to be greater than that of the isovolumic cycle, just in proportion as the specific heat of air at constant pressure is greater than the specific heat at constant volume, which corresponds with the ratio of the figures given in Table II, column 1.

The expression $1 - \sqrt{\frac{T_2}{T_1}}$ for the efficiencies of the isobaric and isovolumic cycles is novel, but applies only to the special case in which the temperatures at the end of adiabatic expansion and compression are equal, which satisfies the condition for maximum output per unit weight of air as the working fluid.

In the Carnot cycle for air, it is quite reasonable that for a given lower limit of pressure and temperature there is for each upper pressure limit a corresponding temperature that gives the maximum output per unit weight of the working substance. If the temperature were increased to such an extent that it would require the expansion to be adiabatic over the entire pressure range in order to reach the lower temperature limit, then there could be no isothermal expansion, no intake of heat and consequently no work.

It will be also noted that it is not alone with air as a working medium that the use of the Carnot cycle involves high pressures in order to utilize moderate temperatures. By a curious coincidence, the temperature given by Dr. Steinmetz as best for an air cycle with 24 atmospheres maximum pressure, corresponds almost exactly with the temperature of saturated steam of the same pressure. And this is why we use superheated steam. We cease to attempt to approach the Carnot cycle at the higher temperatures, and turn to a less efficient one in order to avoid inconveniently high pressures.

Superheat is not theoretically the most efficient means for utilizing great temperature differences, with steam as the working fluid, but for the present it is the most practical means available, and is much better than nothing at all.

Thermodynamics is a very interesting and almost limitless subject, but thermodynamics and practical commercial engineering overlap only to a moderate extent. The cycle of the heat motor is but a small link in the chain of processes involved in converting the energy of fuel into mechanical energy; and if one concentrates too much on this one link, he is apt to contract his field of vision.

The proper selection of a prime mover depends more than anything else on that valuable human faculty that we call "horse sense",—which, like greatness, one may be born with, or may acquire, but which, unlike greatness, cannot be thrust upon him. It may be taken for granted that no manufacturer who has been prominently in business for ten or twenty years is putting out a distinctly bad heat motor.

The steam turbine may, for obvious reasons, without attaining prohibitive dimensions, be made large enough efficiently to utilize exceedingly low pressures and temperatures, when the low temperatures are available, but it does not follow that it must necessarily be so made. Because of the especial adaptability of the turbine for using large volumes of steam, and the excellent way in which the reciprocating engine handles steam at the small volumes consequent on high pressures, a high-pressure reciprocating steam engine compounded with a low-pressure steam turbine often presents a very attractive combination.

The mechanical difficulties involved in the attempt to utilize the full range of expansion of high-pressure steam in a single cylinder of a condensing engine, have long been recognized as being at least fully as important as the thermodynamic difficulties. We are not confronted alone by high mechanical stresses but by prohibitive clearances, unendurable leakage losses, and the impracticability of a valve gear for the very short cut-offs that would be necessary.

The pressures in gas engines,—say 25 to 30 atmospheres—have not been found unduly difficult to cope with. The heavy reciprocating masses smooth down the peaks of pressure so that in general the mechanical stresses are well within the limits of conservative engineering practice. Gas producers are now obtainable which may be operated with the same degree of efficiency, reliability and continuity as the best boiler plants.

It can scarcely be claimed that one type of prime mover demands a higher grade of attendance than another, or that there is any serious difference in reliability as between the several types. The skill required to obtain the best results from the turbine or the gas engine, as compared with that required for getting equally good results from reciprocating steam engines is different in kind, but not necessarily in degree. Skilled attendants for steam turbines and gas engines are more uncommon than for reciprocating steam engines, but that is because we have been training attendants for reciprocating engines for 150 years, and the school has been a very large one. We have been training gas-engine and steam-turbine attendants for perhaps less than 30 years, and our educational facilities have until recently, been exceedingly limited in extent. There are dozens of men who can detect symptoms of trouble in reciprocating engines, and who can correct troubles before they become serious, to every one man who can do the same for a gas engine or a steam turbine. Yet the skilled gas-engine or steam-turbine attendant might not be able to display much resource in an installation of reciprocating steam engines. When we see a particularly fine piece of work, do we compliment the workman, or his tools? When we hear of an especially good record of electric power station service, both as regards reliability and overall economy, shall we compliment the prime mover, or the manager? The final overall efficiency and reliability of the plant depends on the human factor as well as the mechanical factor. The variations possible in the latter—considering, of course, only reasonably modern and accepted types of equipment—are so small as to be over-shadowed in the variations of the former.

Always the two-thousand-year-old parable of the talents is recalled to us. The talents differed not in goodness, and yet they produced widely different results, according to the respective efficiencies of the men to whom they were entrusted. And the parable would have been more realistic, and more in keeping with what we often see in our daily contact with the great and growing electric power industry, if he who was entrusted with only a single talent had, by his energy and foresight, equalled or surpassed him that was entrusted with ten.

David B. Rushmore: Almost every engineer has to do with a prime mover in one form or another, and questions arise in that connection, whether the engineer is an operating engineer, or connected with a manufacturing company, or whoever he may be. One of the questions to be considered is, what shall be called the output or the rated capacity of these machines? This question nearly always arises in a comparison between machines manufactured by different concerns, where the basis for the rating has not been definitely fixed.

In the steam engine, for example, which is one of the oldest forms, we have a fairly definite idea when we speak of so many horse power output for the engine. The turbine, which is not as old, has a variable overload capacity, or an overload capacity not always expressed in the normal rating of the machine, and so there is considerable lack of definiteness which is sometimes confusing.

The gas engine is peculiar in a certain way, in that the rated output of the gas engine is one with a very small overload capacity. In comparing estimates on certain installations, which I have recently looked over, the engineers did not bear this fact in mind, and in certain industrial establishments which are now in process of construction, an active discussion is taking place as to which is the more desirable form of prime mover to use, in order to generate electrical energy from the gases of blast furnaces. This is the particular point I desire to speak on, not to reach any conclusion, because there is no conclusion which can be had at present. The factors which are going to form this conclusion are those not to be reached in a way which is positively acceptable.

A steam turbine may have a thermodynamic efficiency under the conditions of operation which will approximate 13 or 14 per cent. A gas engine under the conditions of operation may reach 24 or 25 per cent. The output in the case of the gas engine is approximately 100 per cent more than we will get in the other case, and naturally, as has been the fact, people have wished this output, but the lowest cost of electrical energy is not the real thing that the owners of this establishment are after. It is the lowest cost of their output, and the factors which should be introduced into the problem are depreciation, repairs, and interruptions to service. In making a final comparison we must have more or less of that information at hand. Reliability insurance, which Dr. Steinmetz speaks of, appears not exactly in the way in which he has presented it, but in the choice of machinery to be used. If we have engines which must be out of service frequently, if we have engines with very high charges for repairs, if we have engines on which the depreciation is very high, if we have an installation the cost of which is from 50 to 100 per cent greater in one case than in the other, a thermodynamic efficiency which is twice in one case what it is in the other, will not make up for the influence of the other factors.

Calvert Townley: I understand that our respected President and some of his advisors have inaugurated a movement at

Washington intended to preserve the water-powers of the country for the general public. It is proposed that when water powers are developed there shall be a payment made to the government proportionate to the output of such powers. I take this opportunity, therefore, to say that I believe such a course in many cases will absolutely prevent the development of water-powers, and, instead of benefiting the general public by swelling the government income, will retard the advance of any industries that might be assisted by cheap power.

I presume that the idea of a charge is born of the thought that water-powers are enormously profitable to the owner, and that he should not be allowed to monopolize our country's natural resources for private gain. It has been my experience in New England, gained both from operating some water-powers and in examining the commercial feasibility of others with a view to possible development, that in competition with steam, the majority of power developments are so heavily handicapped by fixed charges and operating difficulties as to make their commercial development of doubtful interest.

There is a decided similarity in many of the conditions affecting water-powers in the several New England states; for example, the rain-fall, the run-off per square mile of drainage area, and the relations between maximum, minimum and average flow. We can be fairly sure, for example, that the maximum flow of any stream will be about two-and-one-half times its average flow, not considering spring freshets, and that the minimum flow will sometimes drop to the vanishing point. Let us examine then the fixed charges of a water-power which it is proposed to develop for the sale of electric energy in competition with that produced by steam. Assume that this power can be developed to 80 per cent of the maximum flow of the stream at a cost of $100 per kilowatt capacity, including hydraulic works, electric machinery and transmission line. This is a low figure for many water-powers, but is purposely so chosen for purposes of illustration. We cannot safely contract to deliver a peak load greater than the average flow of the stream. Therefore, if it costs $100.00 per kw. capacity to develop 80 per cent of the maximum flow, which flow is two-and-one-half times the average flow, the development cost for the average flow will be $200.00 per kw. The load-factor must next be considered. It is a fortunate company that can show a load-factor as high as 50 per cent,—that is to say, where the average 24-hour load is as much as one-half the peak load or station capacity. This means, then, that for the average current sold, which is really the unit that has to carry the full fixed charge, the investment is not $200.00, but $400.00 per kw.

In time of low water, the company must still be prepared to carry its peak load; that is, a load equal to the average flow of the stream. Last year the minimum flow was not to exceed 25 per cent of the average, requiring, therefore, a relay of at least 75 per cent from some source other than the water-power itself. If this source be a steam plant, and the cost of such plant be taken at $100.00 per kw. rated capacity, there must be added $75.00 per kw. to our investment on which to base fixed charges, making the total development cost for each annual kw. sold, $475.00, or at only five per cent interest, not including depreciation, an annual cost of $23.75 over and above all operating expenses.

By contrast, a steam plant costing to build $100.00 per kw., and having a capacity equal to the peak load and operated with the same load-factor previously assumed (50 per cent), must provide for fixed charges on $200.00 only, or $10.00 per year, taking the same interest as before. This shows at once a handicap of $13.75 per year which the hydraulic plant must overcome by lower operating expenses, before the water-power is on all fours with the steam development. Where the load-factor is lower, or the cost of the hydraulic development is greater per kw. capacity, or where depreciation is to be provided for, or a larger steam relay necessary, any or all of which conditions are frequently met, the hydraulic plant labors under a still greater disadvantage.

It will readily be seen, I think, without pursuing this comparison further, that any arbitrary governmental tax or charge will lessen the attractiveness of water-power investment, and will so seriously handicap the development of a great number of powers as to entirely destroy their commercial availability.

My excuse for speaking of these obvious facts, which are known to many of you, is that there seems to be an entire lack of knowledge on this question by a considerable portion of the general public, resulting in the danger that unfortunate laws may be enacted tending to injure seriously an industry in which many of us are interested. Therefore, if you, as engineers, will, as opportunity offers, take pains to see that the fundamentals are understood, you can have a material effect on forming proper and intelligent public opinion.

Ernst J. Berg:* In concluding the discussion I shall not try to defend Dr. Steinmetz's paper nor the premises used in his arriving at the thermodynamic efficiencies, especially since I feel that it will give him great pleasure to do so himself. I will, however, add that when reading his paper this afternoon I found it most instructive and valuable. No doubt I have seen these thermodynamic cycles described in text-books, but it is so many years ago that I have forgotten them, and I am sure that they were not given in the concrete form that Dr. Steinmetz has presented. I know that there are other members in the same situation, and to them as to me the paper has a charm of novelty and is very interesting.

Dr. Steinmetz says, if I am not mistaken, that the limits of pressure and temperature chosen by him in working out the thermodynamical cycles might be somewhat varied, but he also states that the conclusions will not be much affected by such variations as long as they are reasonable, and I believe him. A temperature limit of 800 degrees cent. seems as high as could well be used, since I believe this to be the temperature at which the cylinders begin to be dull red.

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* In the absence of the author on account of illness, the paper was presented in abstract by Mr. Berg, who replied as follows:

As to the pressure, it seems that 24 atmospheres or about 350 lb. is as high as is good for conservative engineering, therefore, I find nothing wrong about the assumption. The efficiencies are finally based upon cycles which give the maximum work for given cylinder dimensions, which seems also very fair. When finally the tables showed that the efficiencies, mechanical as well as thermoydnamic, were consistent with known facts, I was satisfied there could not be any criticisms on these scores.

Professor Lucke said that there were no conclusions given in the paper. That is true. I do not think Dr. Steinmetz wanted to give any, I do not think he wanted to say that any given cycle or type of prime mover was best. He made a fair comparison between the various prime movers.

Charles P. Steinmetz (by letter): As far as I can understand, Professor Lucke's lengthy but rather unintelligible discussion is a general denial. In short, he says: the assumptions of the paper are wrong, the methods of reasoning are wrong, and the conclusions are wrong; while the second speaker, Mr. Longwell, explains in great detail, that the assumptions of the paper, the methods of reasoning, and the conclusions are old and well-known, and their correctness demonstrated in every elementary text-book, so much so that they do not need to be stated. As the statements of these two speakers thus contradict each other, I do not need to discuss them further, but merely desire to point out to Professor Lucke that the study of typical thermodynamic cycles is not useless, because no heat engine exactly follows any of these cycles. In electrical engineering also, no existing transformer exactly agrees with the typical transformer diagram, nor any existing transmission line with the equations of transmission lines. Even Ohm's law is not rigidly obeyed by any industrial circuit, as secondary phenomena, such as temperature changes, always occur. Nevertheless, we use these laws and methods in design and calculation, and the history of electrical engineering has amply justified us. Phenomena of nature are always complex, and thus can never agree completely with any typical representation; but it is the province of the engineer to find the closest theoretical representation of the actual facts, and then bridge over the gap by engineering judgment.

While Mr. Longwell desires the thermodynamic cycles omitted from my paper as obvious, for Professor Lucke I should have added an extensive discussion on the relations of the theoretical thermodynamic cycles to the actual cycles in heat engines. I have thus chosen the middle ground, illustrated the reasoning on the typical thermodynamic cycles, and left it to the intelligence of the reader to realize that the actual engine cycles are intermediate between, and combinations of, the typical cycles, and hence are covered by the results of the typical cycles.

Professor Lucke's statement, that the temperature range has no effect on the efficiency of the thermodynamic cycle, obviously is wrong. If his idea of gas-engine design is to put as much heat into the cylinder as possible, and see what power he gets out of it, and he does not care to know what the temperature is; this obviously does not prove that the temperature is immaterial.

In general, an efficient designing engineer endeavors to know not only what is put into, and what comes out of an apparatus, but still more, what takes place in the apparatus. The rapid advance of electrical engineering is to a large extent due to the fact that the designing electrical engineer was not satisfied merely to put as much mechanical power into the machine as possible, and measure whatever electrical output he got, but has carefully studied the internal reactions of the apparatus, and thereby was enabled intelligently to choose and predetermine the actions, with the result that the waste of power in electrical apparatus has been reduced to a negligible quantity.

However, Professor Lucke's method of gas-engine design, by putting as much heat as possible into the cylinder, is merely a repetition, in different words, of the assumption which I made in my paper for the air cycles. These cycles I consider for the conditions of maximum output, where the greatest amount of heat is put into the cylinder, which still increases the output.

The claim made by Professor Lucke and Mr. Longwell, that the assumptions made in my paper are arbitrary, and by a different set of equally justified assumptions any other conclusion can be reached, is wrong; the assumptions made in my paper are not arbitrary, but, as proper in such investigations, I have chosen the conditions most favorable for each case. That is, where the efficiency or output increases with the temperature, I have chosen the highest temperature; where the efficiency or output increases with the pressure, I have chosen the highest pressure permissible by reasonably conservative design. The only feasible variations of the assumptions thus are minor changes: some engineers may consider 24 atmospheres too high, and prefer 20 atmospheres as a more conservative limit, while another engineer may be willing to allow pressures up to 30 atmospheres. As I have stated in my paper, however, the results and the conclusions, are not appreciably changed by any reasonable change of my assumptions.

Incidentally, Mr. Longwell is mistaken in his statement that equality of the two intermediate temperatures of the air cycle fulfils the conditions of maximum output per unit weight of air. This happens to be the case for the two cycles specifically discussed in my paper, but not in general. For instance, for the air cycle of constant pressure admission and constant volume exhaust, in the conditions of maximum output—which is the assumption of my paper—the two intermediate temperatures are not equal. His statement that the efficiency of the isobaric cycle of saturated steam is that of the Carnot air cycle between the same temperature limits, is not quite correct either, but the efficiency of the steam cycle is slightly lower, though the difference is usually small.

My paper discusses the economy of the production of electric power from nature's stores of energy to the switchboard. If one corporation develops the water-power, another one uses it by buying the water of the former. This obviously does not change the cost of development etc., and you do not get water-power without cost of development, as Mr. Longwell seems to think, if you let somebody else develop the water-power, and pay him for the cost of development in the price of water bought of him. The economic considerations from the station switchboard to the light radiated from the customer's lamps, are equally important, as Mr. Longwell states, but they are not the subject of my paper.

I am sorry that Mr. Longwell thinks the kilojoule a new unit: the kilojoule, or kilowatt-second, is, and has been for some decades, the international unit of energy, used throughout the world, not only by the electrical engineers, but also by other engineers, such chemists as Ostwald, and others, with the exception of that rapidly dwindling group of mechanical engineers in the two English speaking countries, who still prefer to measure distances by what in the earlier middle ages was considered the proper length of a king's foot, and to measure temperatures by a scale using as zero the lowest winter temperature of Northern Germany, and as 100 degrees an erroneous measurement of blood heat (Fahrenheit). While the two English speaking nations have not yet reached the courage of completely freeing themselves of the curse of the ancient "English system" (so-called because all the other civilized nations have long ago discarded it), with its seven or more incompatible units of length* and other curios, I would not impose such a system on the American Institute of Electrical Engineers which already years ago has gone on record as endorsing the metric system, by a ballot vote of over 90 per cent majority.

It is true, that in the English system, when expressing the energy of fuel in British thermal units, the output of the boilers in pounds of steam per hour, the indicated energy of the engine in foot-pounds, and the output at the switchboard in kilojoules, the numerical values are not so disturbing to the self-satisfaction of the engineer as when throughout the entire transformation, the energy is expressed by the same units, and the inefficiency of the performance thereby shown in all its nakedness.

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* **Foot, mile, chain, rod, fathom, knot, yard, etc.**

But, whether such a hiding of the inefficiency is to the advantage of the art, is questionable.

In regard to Mr. Longwell's objections to my statement that electric energy is a secondary form of energy, I shall be glad to withdraw this statement, as soon as Mr. Longwell will have succeeded in harnessing the thunder cloud, and in lighting the cities from nature's stores of electricity, from lightning, or from the earth currents, or whatever other of nature's stores of electricity he has in mind for industrial use.

A paper presented at the 235th meeting of the American Institute of Electrical Engineers, New York, March 12, 1909.

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THE INDUSTRIAL APPLICATION OF THE ELECTRIC MOTOR, AS ILLUSTRATED IN THE GARY PLANT OF THE INDIANA STEEL COMPANY*

BY B. R. SHOVER

Introduction and historical. Twenty years ago electricity, except for lighting purposes, was virtually unknown to the iron and steel industries, while to-day in all the steel works in this country it is used as a motive power for most of the auxiliary machinery, from the ore docks to the loading beds. The electric drive is utilized in ore unloaders, ore bridges, car dumpers, bin-filling cars, scale larries, blast-furnace skips, hot-metal mixers, electric cranes of all sizes and descriptions, open-hearth charging machines, ingot buggies, gas producers, roller tables, lifting tables, transfers, hot-bed apparatus—in short, a multitude of machines too numerous to mention here. This development has been such that it would probably be no exaggeration to say that the steel industry in this country would never have reached its present proportions without the use of electric motors. As a further gauge of progress, it is significant that the larger electric manufacturing companies have been forced to establish special departments to look after the business of the steel industries.

Development of the direct-current motor. The first application of electric power to the steel-mill industry was by means of the direct-current motor. In a historical way the following remarks may be of interest, but the absolute accuracy of the dates given the author does not wish to be held entirely responsible for, though all possible care has been taken to verify them.

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* The magnitude of the work in this plant has been such that without the hearty coöperation of the staffs of all the electrical manufacturing companies (practically all of whom have contributed to the work) it would have been impossible to obtain the results herein outlined. The author is, therefore, glad of this opportunity publicly to acknowledge the valuable assistance which they have given him and his company in this work.

In 1882 the first electrical installation in any steel plant in the United States was made at the works of the Edgar Thomson Steel Co., at Bessemer, Pa. It consisted of a two-light Brush arc machine.

In 1889 an electric traveling crane was installed at the works of the Pencoyd Steel Co. near Philadelphia.

In 1891 a 50-h.p., 250-volt, compound-wound generator was installed in the Edgar Thomson Steel Co. works. This machine was used to supply current for an experimental crane over the heating furnaces at the blooming mill.

In February, 1893, the first motor-driven roller table was put in operation at the Homestead works of the Carnegie Steel Co.

On February 9, 1895, the first mill having all its roller tables motor-operated was started by the Ohio Steel Co., of Youngstown, Ohio.

In the early days belt-type and street-railway motors rewound for 250 volts were all that were available, but the severe service to which this apparatus was subjected led the manufacturers to strengthen it and to design new motors to meet the requirements; so that the steel industries both assisted in and profited by the general improvement of electrical machinery. One result of these requirements has been the development of the so-called mill motor. This motor has a heavy cast-steel frame, a large armature shaft, which can be replaced without disturbing the winding, the minimum number of bolts, ample air-gap, and fire-proof winding throughout. So successful has this type of motor proved that it is now being used almost exclusively, even on traveling cranes, regardless of the fact that the entire crane and runway must be made much heavier in order to carry the additional weight.

In order to appreciate the importance of such apparatus to the steel manufacturer it must be understood that the real efficiency of any machinery used in the industry is indicated by the amount of steel shipped per day or year. A motor of higher engineering efficiency that causes shutdowns, and consequent decrease of profit, is not nearly so efficient as a motor that operates 24 hours a day and 365 days a year, if necessary, practically without stopping. This feature is considered so important that in one plant the superintendent of the electrical department requires a special report from his mill foremen whenever the mill is delayed more than 3 minutes by changing the armature of a table motor. The steel works electrical engineer has long since recognized that the mills are built to manufacture steel, and to be successful electrical apparatus must meet the requirements, no matter how severe. To the credit of the engineers be it said that the number of absolute failures to operate any of the apparatus has been very small indeed.

Development of the alternating-current motor. The coming of the induction motor found the steel mills equipped with direct-current apparatus, but the induction motor is so well suited for much of this work that it has been gradually introduced into the field, until to-day it forms a considerable part of the aggregate horse power used in the steel industry. The following historical notes represent the more important steps in this development.

In 1900 the Joliet works of the Illinois Steel Co. installed a 250-volt direct-current synchronous converter operating from a 2200-volt, three-phase supply. the power being furnished by an independent power company.

In 1902 the Pennsylvania Steel Co., of Harrisburg, Pa., installed an 11,000-volt transmission system.

In 1903 the first induction motor used in the steel industry was installed at the Joliet works of the Illinois Steel Co.

In June, 1904, the South works of the Illinois Steel Co. installed a synchronous converter and step-up transformer to operate a 2200-volt transmission line and in September of the same year a 4000-kw. power plant, generating at this voltage, was installed. About the same time this voltage was stepped up to 22,000 volts for transmission to the cement works at Buffington, 12 miles away.

In December, 1904, the first installation of 6600 volts for interworks use was installed by the Lorain Steel Co. This voltage now seems to be the favorite for use in the entire steel industry, as it has been employed in many of the late installations.

The application of electric motors to the roll trains. While the United States has led in the application of electric drive to auxiliary machinery, Europe has pioneered the way in its use for driving roll trains. In the different European steel plants there are to-day about 230 motors with a normal capacity of 19,000 h.p. and a maximum capacity of 41,000 h.p. used for electric drive of non-reversing roll trains. In addition, one noteworthy installation is that of a 10,500-h.p. reversing outfit at the Hildegardehütte mine.

The first application of motors for driving roll trains in this country was made at the Edgar Thomson works of the Carnegie Steel Co. in October, 1905, where two three-high roll trains for rolling small rails were operated by 1500-h.p., 220-volt, direct-current motors. The speed of these motors is varied by shunt-field resistance from 100 to 125 rev. per min. The success obtained by this installation has stimulated the installation of similar outfits elsewhere.

In June, 1907, the Illinois Steel Co. put in the first and only reversing-mill drive that has been installed in this country. The mill, a 30-in. universal plate, is direct-coupled to two 2000-h.p., 150-maximum rev. per min., 575-volt, shunt-wound motors mounted on one shaft; 2200-volt, three-phase, 25-cycle, alternating-current power being used to drive a motor-generator set consisting of a 1300-h.p. motor and a 3000-kw., 600-volt, direct-current generator. On the same shaft is mounted a flywheel 100 tons in weight, 13 ft. 2 in. in diameter, the whole making 375 synchronous rev. per min.

In August, 1907, at the same works, a rail mill for rolling small rails similar to those rolled at the Edgar Thomson works, was put in operation. The roll trains here, however, were driven by 2200-volt concatenated motors. The primary motor has a capacity of 1200 h.p., and runs at 120 rev. per min.; the secondary motor is 600 h.p., and runs at 82 rev. per min. In ordinary operation the resistance in the secondary motor is so adjusted that the combined speed of the two varies between 60 and 80 rev. per min. according to the character of material rolled.

The use of a storage battery. Another electrical device which has only recently been used in the steel industry is the storage battery. On March 27, 1904, the first installation of this nature was made at the Ohio works of the Carnegie Steel Co., Youngstown, Ohio. This battery had a capacity of 1600 ampere-hours and was used for regulating the load on a direct-current station. On April 29, 1905, the capacity of this battery was increased 50 per cent. The success of this installation was so marked that batteries of considerable size were installed at the Lukens

Iron & Steel Co., Coatesville, Pa. Three large batteries were also installed at the Illinois Steel Co., South Chicago; one at the Carrie furnaces of the Carnegie Steel Co., Rankin, Pa.; one at the Duquesne works of the Carnegie Steel Co., and the largest of all at the Edgar Thomson works of the Carnegie Steel Co., Bessemer, Pa.

Inception of the Gary plant. For several years the United States Steel Corporation had recognized the necessity of supplying the increased demand for its product throughout the West. To give an idea of the rapidity with which the demand for these products had grown, the total product of steel in the United States in 1894 was 4,000,000 tons; in 1895 this product had increased to 6,000,000 tons; in 1900 to 10,000,000, and in 1906 to 23,000,000 tons.

Fig. 1.—The Elbert H. Gary anchored for the first time under the unloaders.

The constantly increasing proportion of this material used throughout the West necessitated the location of additional manufacturing facilities closer to the point of consumption. As none of the existing plants had ground enough on which to instal the required increase, it was decided to build an entirely new plant, to be designed so as to embody all the features that would ensure economical production. The site chosen is at the extreme south end of Lake Michigan, about 26 miles from the center of Chicago. It consisted of about 10,000 acres of sand dunes absolutely uninhabited, and covered by a growth

FIG. 2.—The first bucket of ore removed from the Elbert H. Gary

of scrub oak, pine, and cactus. The advantages of this location consist of lake transportation, splendid railroad facilities, and cheap land.

The governing feature in the design of the plant was economy. To this end the plant was planned so as to get the best possible transportation facilities for the material during its various stages of manufacture throughout the entire works. To add to the economy the design included the use of blast-furnace gas in gas engines, driving electric generators to furnish electric power for use wherever its application was practicable.

In the general design all features were incorporated which had proved satisfactory elsewhere, it being the intention to exploit only the new applications and schemes which were absolutely necessary to the construction of such a works and thus minimize, as far as possible, experimental apparatus.

Layout of the plant. The layout of the plant has been so well described in several recent publications that detailed description need not be given here.

Present condition. Of the plant as planned, the slip and docks are complete; one-half of the ore yard and its machinery, including the ore bins, is finished; also one group of blast furnaces—of which three are in blast—with its complement of blowing engines and gas-washing plant, and the central pumping station. The pig-casting machines have all been in operation for some time. Four more blast furnaces, with their auxiliary buildings, are about 75 per cent completed. The No. 3 electric power station and storage-battery are ready for operation; the turbines in No. 2 power station have been in operation since July, 1908, and the remainder of the station is rapidly being completed. One-half of one open-hearth plant is in operation, a second plant is practically complete, and foundations are ready for a third. The entire shop group has been in operation for more than a year. The rail mill has been tried out. Most of the machinery has been installed in the billet mills. The foundations are laid and part of the structural material of the merchant mills is already erected.

In the part of the works now complete there are 110 electric traveling cranes with an aggregate lifting capacity of 3812 tons, 22,025 h.p. in direct current, 5312 h.p. in 440-volt alternating current; 27,000 h.p. in 6600-volt alternating-current motors have already been operated. About an equal aggregate number of horse power will be required for the operation of that part of the plant now under construction, and still more for parts which are at present being designed.

Of the transmission line 31,000 ft. has been completed, 300 tons of copper wire being strung over the 281 supports. In addition to this, a total of 500 tons of copper wire and cable of all sizes is used in the distribution of current to motors, lights, etc., 19.5 tons of copper bar on the main distribution towers directly outside of the station and 100 tons of bar and cable inside the station.

Electric power station. For this part of the plant it is intended to use the gas available from eight blast furnaces. On account of the large amount of current, the especially large number of circuits and units, and also to make the operation more reliable, this plant is divided into two sections, which are called power houses No. 2 and No. 3, respectively.

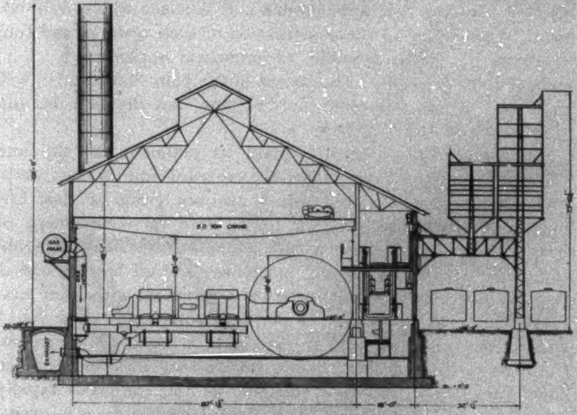
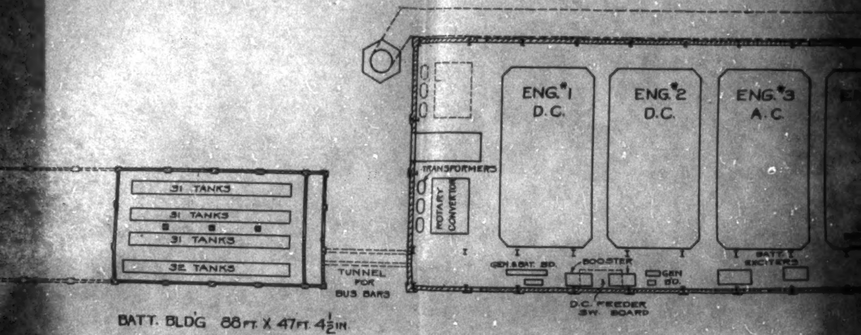
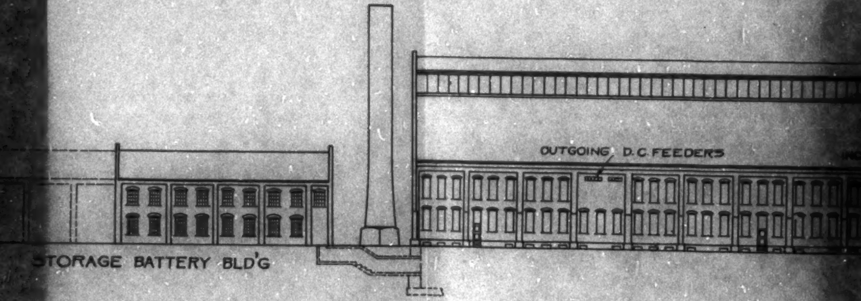


FIG. 4.—Cross-section of power station.

The eight blast furnaces producing 3600 tons of pig iron per 24 hours will give a total of 22,450,000 cu. ft. of gas per hour. Thirty per cent, or 6,750,000 cu. ft. of this gas is used for heating stoves; 7.5 per cent, or 1,700,000 cu. ft. is used under the boilers to furnish steam for spare steam engines, pumps, and miscellaneous heating; 2.5 per cent, or 600,000 cu. ft. is necessary for operating the gas washers; 12.5 per cent, or 2,800,-


31 TANKS
31 TANKS
31 TANKS
32 TANKS
TUNNEL FOR BUS BARS
BATT. BLD'G 88 FT. X 47 FT. 4½ IN.
TRANSFORMERS
ROTARY CONVERTER
ENG. #1 D.C.
ENG. #2 D.C.
ENG. #3 A.C.
GEN. & BAT. BD.
BOOSTER
GEN BD.
D.C. FEEDER SW. BOARD
BATT. EXCITERS


OUTGOING D.C. FEEDERS
STORAGE BATTERY BLD'G

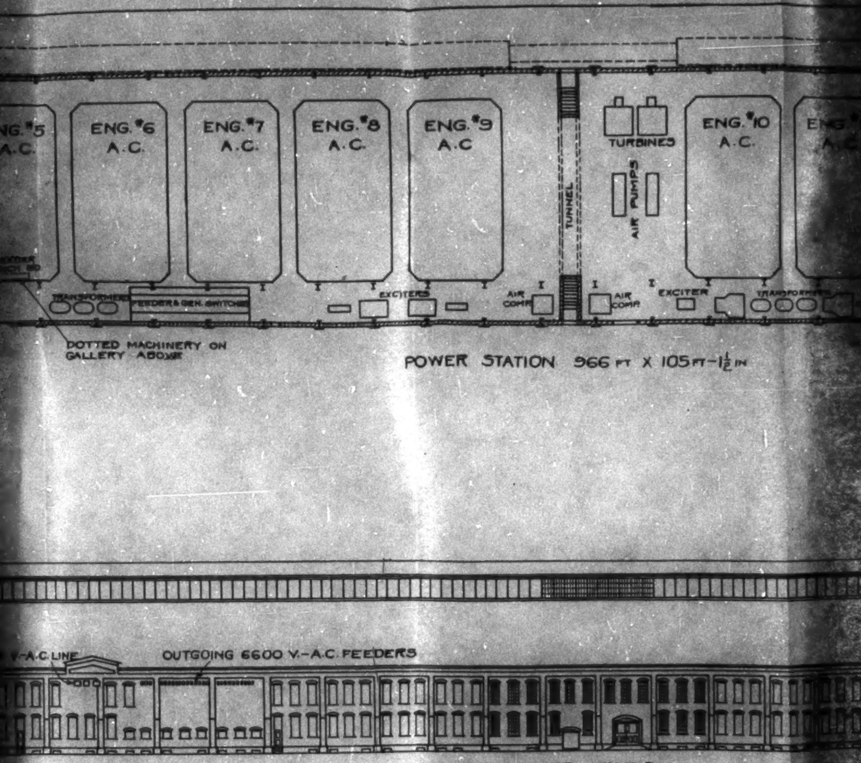
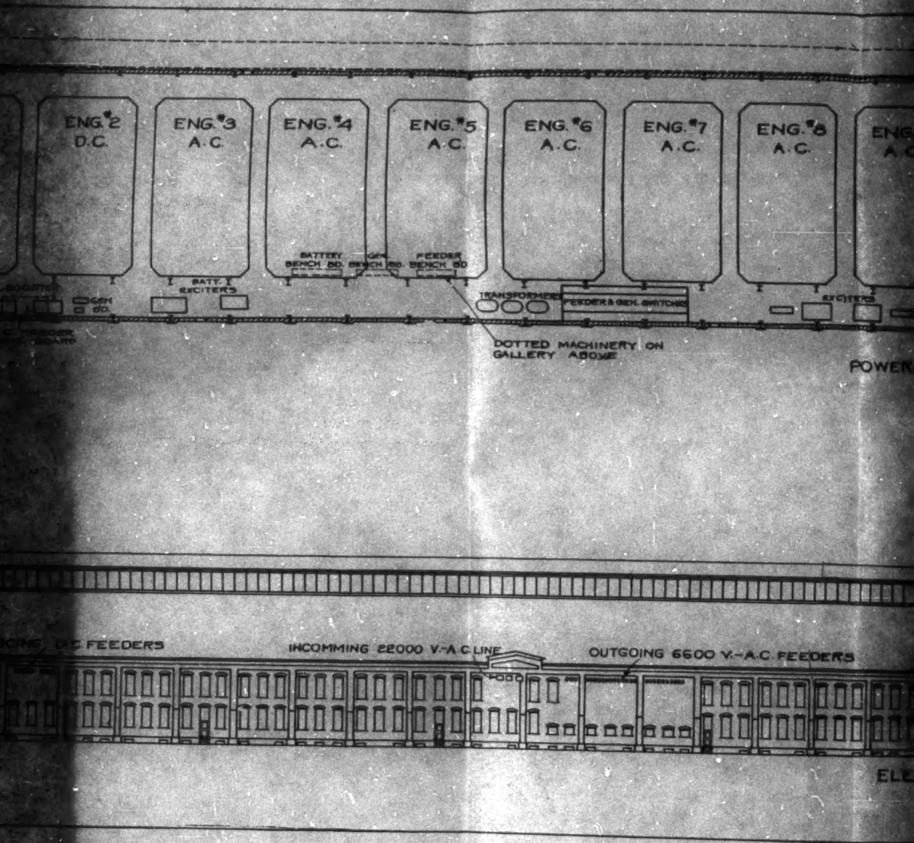

ENG. #5 A.C.
ENG. #6 A.C.
ENG. #7 A.C.
ENG. #8 A.C.
ENG. #9 A.C
TUNNEL
TURBINES
AIR PUMPS
ENG. #10 A.C.
TRANSFORMERS
FEEDER & GEN. SWITCHES
EXCITERS
AIR COMP
AIR COMP
EXCITER
TRANSFORMERS
DOTTED MACHINERY ON GALLERY ABOVE
POWER STATION 966 FT X 105 FT-1½ IN
V-A.C. LINE
OUTGOING 6600 V.-A.C. FEEDERS
ELEC. POWER STATION

Fig 3.—Plan and elevation of the power stations 2 and 3


ENG. #2 D.C.
ENG. #3 A.C.
ENG. #4 A.C.
ENG. #5 A.C.
ENG. #6 A.C.
ENG. #7 A.C.
ENG. #8 A.C.
ENG.
BOOSTER
GEN BD.
BATT. EXCITERS
BATTERY BENCH BD.
GEN. BENCH BD.
FEEDER BENCH BD.
TRANSFORMERS
FEEDER & GEN. SWITCHES
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BOARD
DOTTED MACHINERY ON GALLERY ABOVE
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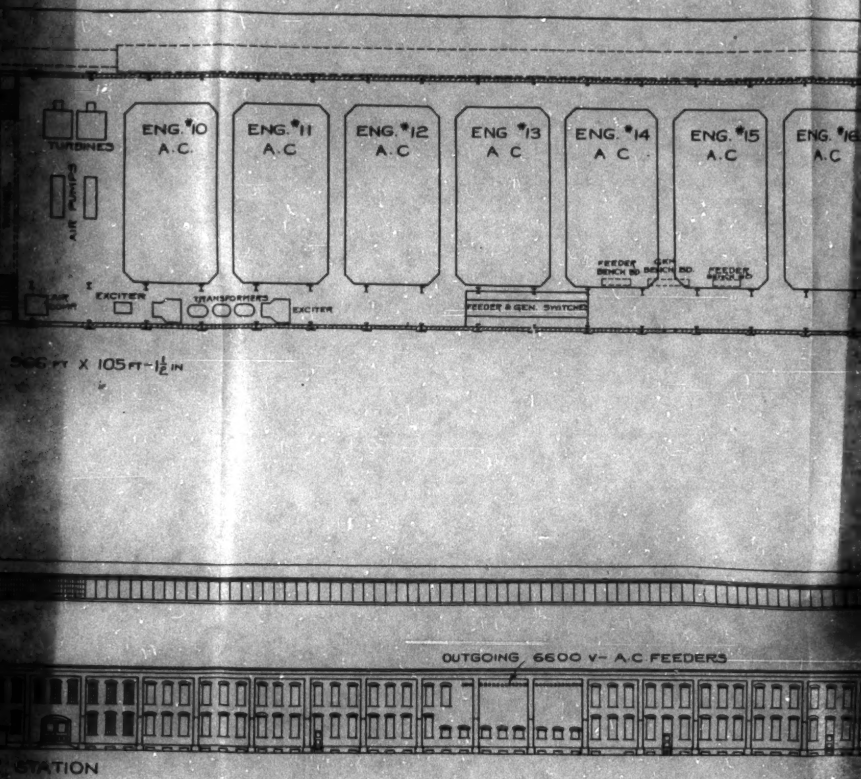
OING D.C. FEEDERS
INCOMMING 22000 V.-A.C. LINE
OUTGOING 6600 V.-A.C. FEEDERS
ELE

Fig 3.—Plan and elevation of the power


TURBINES
AIR PUMPS
ENG. #10 A.C.
ENG. #11 A.C
ENG. #12 A.C
ENG #13 A C
ENG. #14 A C
ENG. #15 A.C
ENG. #16 A.C
AIR COMP.
EXCITER
TRANSFORMERS
EXCITER
FEEDER & GEN. SWITCHES
FEEDER BENCH BD
GEN BENCH BD.
FEEDER BENCH BD
566 FT X 105 FT-1½ IN
OUTGOING 6600 V- A.C FEEDERS
STATION

000 cu. ft. is used by the blast-furnace blowing engines; 2.5 per cent, or 600,000 cu. ft. for auxiliary use in connection with these engines. The remaining 45 per cent, or 10,000,000 cu. ft. per hour, is available for power purposes.

If estimated at 90 B.t.u. per cubic foot and 10,000 B.t.u. per brake horse power, this gas is equal to 110,000 brake horse power in gas engines.

There are installed in No. 2 and No. 3 electric power stations a total of 17 gas engines each rated at 3000 h.p., but capable of about 50 per cent overload. It will therefore be seen that only approximately 50 per cent of the available power as calculated will be used in this station. This allotment will make allowance for furnaces out of blast, and for shortages of gas due to troubles that are liable to occur in furnaces during operation.

The electrical equipment of power houses No. 2 and No. 3 comprises fifteen 2000-kw., 6600 volt, three-phase, 25-cycle alternating-current units, two 2000-kw., 250-volt direct-current units—all driven by gas engines—and also two 2000-kw. alternating-current turbine units.

The gas engines. The gas engines are horizontal twin tandem, double-acting, running at 83⅓ rev. per min. The cylinders are 44 in. in diameter by 54 in. stroke. The floor space occupied by each engine and generator is 74 ft. by 39 ft., with total approximate weight of 1,700,000 lb. The largest piece in the engine is the bed plate, which weighs from 90 to 95 tons. The flywheel is 23 ft. in diameter and weighs 200,000 lb.

Turbines. The two turbines are rated at 2000 kw. each, and were installed primarily for use in the construction of the plant and to furnish power for starting up. It is also expected that they will assist materially in the regulation of the station by taking care, to a certain extent, of the sudden peak loads.

The switching apparatus and station wiring were designed for simplicity of control, reliability, and ease of repairs. All apparatus, including that for storage-battery regulation, is controlled at the benchboard. A 250-volt excitation current is used and tie-switches are provided, so that in case of failure of exciter sets, or for starting up after a shutdown, current can be supplied direct from the direct-current station bus-bar.

The direct-current switchboards are all of the single-potential type, with ample space between switchboards of opposite polarity. Individual generator switchboards are used so as to get the protective apparatus as close as possible to the generators.

The alternating-current switchboard is of the double bus-bar type, each bus-bar being protected by an electrolytic lightning arrester. In addition to this protection, each feeder has a multigap arrester.

The 22,000-volt line to the South Chicago works is protected by both electrolytic and multigap arresters and has an automatic oil-switch on both sides of the transformers.

Storage-battery. The installation of the storage-battery was for the purpose of minimizing the fluctuation of load on the generating station. The storage-battery consists of two separate batteries of 125 cells, 73 plates per cell, each battery having a rating of 4320 amperes, with a momentary rating of from two to three times that amount. They are installed in a two-story building located directly north of the power station, the connection between the two buildings being through a tunnel.

FIG. 5.—10,000-ampere remote-control switch.

The direct-current regulation is accomplished by means of two 2500-ampere, 35-volt boosters. The motors and generators of this booster are of the interpole type, controlled by a carbon-pile regulator acting through a motor-driven exciter. The alternating-current regulation is accomplished by means of special 2000-kw. split-pole converters. The regulating current for this converter is supplied by a series transformer in the leg of each generator lead. In turn, these transformers are connected to a totalizing transformer of the compensator type which supplies current to a synchronous motor-driven special synchronous converter. From the direct-current side of this converter is taken the regulating current for the split-pole converter. A special 10,000-ampere remote-control switch, shown in Fig. 5, short-circuits the starting resistance.

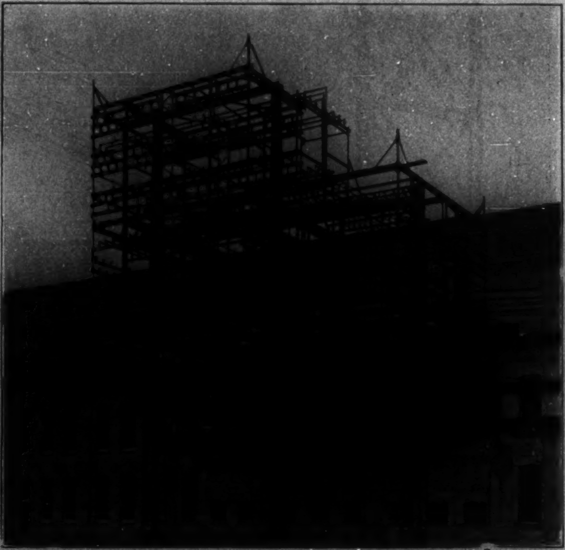


FIG. 6.—One of the special alternating-current wiring towers.

The generator oil-switches are arranged so that the regulating transformer of each generator is short-circuited when that generator is not in service. Connections are also made so that when stations No. 2 and No. 3 are tied together the battery will regulate on both, but should either tie-switch be thrown out, thus disconnecting the two stations, no regulation is possible on station No. 2 and the current transformer in the legs of the generators in that station are at the same time short-circuited. In respect to the average load on the station the regulation of both direct current and alternating current is by remote control from the benchboard.

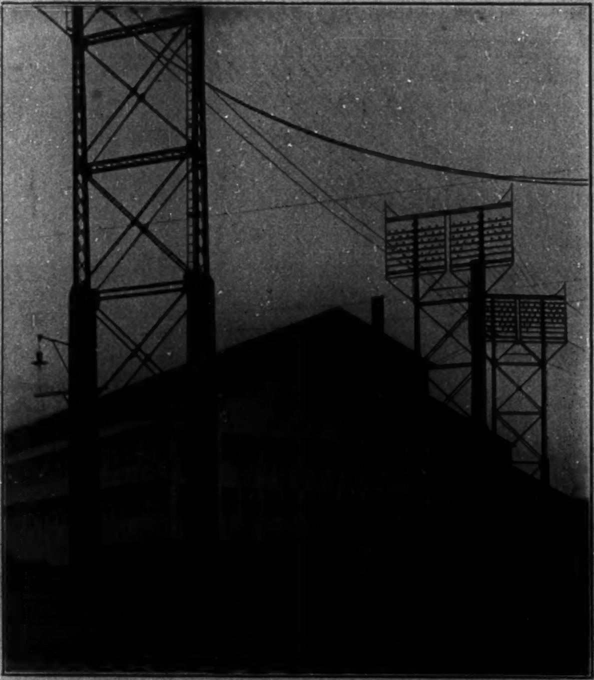


Fig. 7.—The standard 75-ft. straight-line towers.

The transmission system is in duplicate, each section having sufficient capacity to carry the entire load in case of accident to the other sections. The lines are supported upon a steel tower construction made exceptionally heavy on account of the great height of the towers and heavy complement of feeders.

No holes are bored in the cross-arms, which are clipped to the poles, the special malleable pins being clipped to the arms.

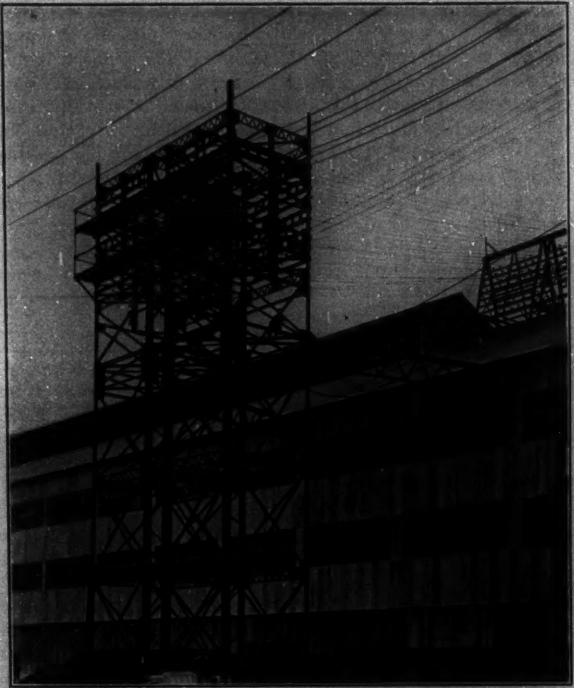


FIG. 8.—Dead-end tower between the rail and the billet mill.

The alternating-current insulators, which are designed for 17,000 volts working pressure, are of three colors to distinguish the phases over the entire works. As will be noted in Fig. 7 and 8, extensions above the pole proper are provided for carrying ⅜ in. galvanized steel ground cables. Each pole is also well grounded.

Sub-stations. There are three sub-stations located as shown on the plan. Sub-station No. 1 is located in the rail mill and consists of four 500-kw., 6600-volt synchronous motors direct coupled to 250-volt direct-current generators. This sub-station normally supplies current for all the direct-current apparatus in the shop group, rail mill, and billet mill.

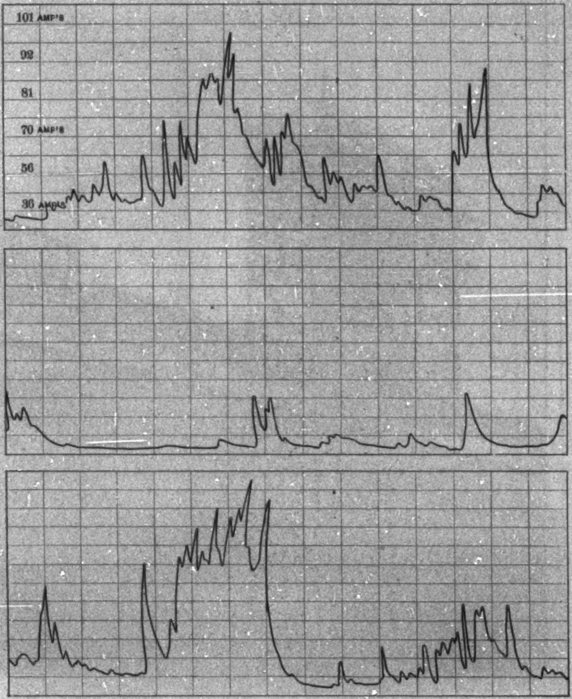


Fig. 9.—Chart showing fluctuating load on a 500 kw. sub-station motor generator set.—To be read from left to right.

Sub-stations No. 2 and No. 3 each have two units, duplicates of those in sub-station No. 1, and normally supply current to the ore unloaders and bridges.

The direct-current power furnished from the two 2000-kw. gas-engine-driven units in the power station is used to supply the direct-current motors for the blast furnaces and open-hearth plants. When the mills are not in operation and only the lights and a few cranes are needed, it will be possible to shut down the sub-station and furnish power direct from the power station. This method of operating will result in considerable saving in operating expense.

Fig. 9 shows the character of the load on this sub-station with one machine in service. A study of this chart shows the nature of load to be such that a storage-battery installed at the sub-station would be of great advantage in its operation. This battery will probably be installed in the near future.

Transformer stations. There are located at various parts of the plant nine installations of transformers for supplying 440-volt, three-phase alternating current. In these stations there are a total of nine 800-kilovolt-ampere, oil-insulated, water-cooled transformers, and twenty-seven 100-kilovolt-ampere, oil-insulated, self-cooling transformers.

PLANT POWER

Central pumping station. All the water for the works is taken from the lake at one point. There are two 10-ft. tunnels running directly west from the middle of the slip, feeding a sump in the pumping station located midway between the gas-washing plants of blast furnaces 8 and 9.

At present there are installed four centrifugal pumps, each of 25,000,000 gallons capacity per 24 hours, pumping against a head of 100 ft. These pumps are driven by three-phase, 440-volt, 500-rev. per min. induction motors.

In order to make this installation as free as possible from interruptions due to electrical troubles, there are two main feeders from the station, one coming from power station No. 2, the other from power station No. 3. Each feeder has its own oil-switch feeding three 800-kilovolt-ampere transformers, and two of the motor-driven pumps are operated from each set of transformers. The bus-bars are provided with disconnecting switches so that either set or both sets of transformers can be operated from either or both main feeders.

Gas-washing plant. In the tabulation of the use of blast-furnace gas there is an allowance of 2.5 per cent for auxiliary machinery. This auxiliary machinery is used in the gas-washing plant. There is one such plant for every group of four blast furnaces. Each gas-washing plant consists of eight washers, driven by 150-h.p., 440-volt, 375 rev. per min. induction motors. These motors are fed from one of the transformer installations, but the secondaries of this transformer station can also be tied in parallel with the transformers in the pumping station, running both as a unit. In case of the failure of one of the sta-

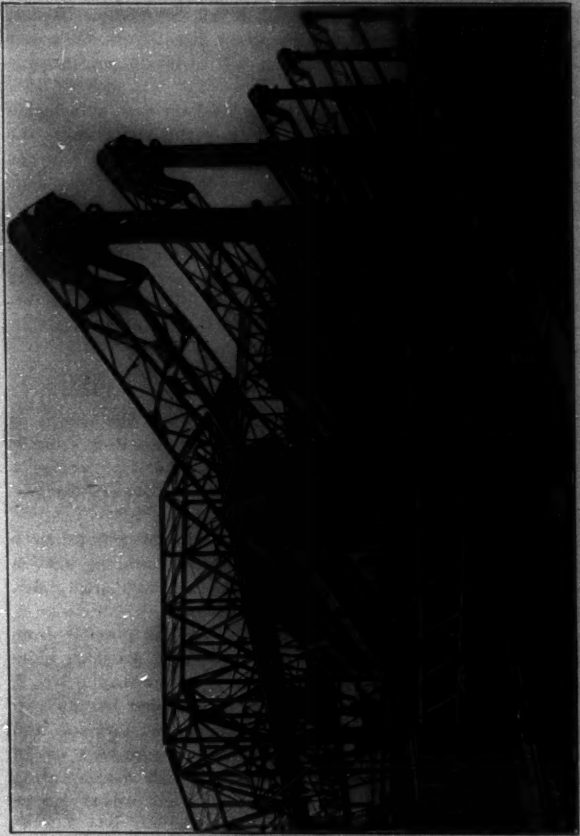
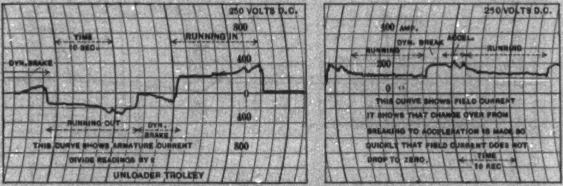


FIG. 10.—Electrically operated ore unloaders.

tions, a part of the pumps and the gas washers can be operated from the other station.

Repair shops. To the south of the rail mill on both sides of the main roadway are located the various repair shops, consisting of machine shops, boiler shop, blacksmith shop, foundry, electric repair shop, carpenter and pattern shop, pattern storage, general store house, brick shed, stable, roll shop, and locomotive house. These shops are operated solely for the repairs necessary to the apparatus throughout the plant, and when in normal operation very little material is purchased from the outside in the finished state, practically all the work being done within the plant. A total motor capacity of 2440 h.p. is installed for operating these shops.

The following description is given in the same order as that in which the raw material is carried through the various processes, until it comes out as finished steel.



FIGS. 11 and 12.—Charts showing the fluctuating load on the ore unloaders. To be read from right to left.

Ore unloaders. Located on the edge of the slip are five ore unloaders, shown in Fig. 10, of 10 tons capacity each. The total weight of each machine is 890,000 lb. The motor equipment of these unloaders is given in the following table:

TABLE A.—ORE UNLOADER

	Horse power	Total horse power	Service	Type
2	25	50	Bucket rotate	Series direct-current
1	50	50	Trolley	Series direct-current
1	85	85	Bucket close	Compound direct-current 75 per cent shunt 25 per cent series
1	100	100	Br. & Car	Series direct-current
1	150	150	Hoist	Compound direct-current 60 per cent shunt 40 per cent series
		435 total		

Total weight 890,000 lb.

The character of the load due to the various motions of these machines is given in the following. Fig. 11 shows the load on the trolley motor on which is used a dynamic brake for stopping. Fig. 12 shows that the change from driving to braking is made so quickly that no record whatever is made of this interruption by the recording instrument. Fig. 13 shows very clearly the power required for hoisting and lowering. With the exception of the car haulage and bridge motion, all motions of the unloader are controlled through remote-control automatic magnetic torque-limit controllers. The master controllers for operating these motors are located in the leg of the unloader, so that the operator who rides with the bucket not only has a clear view of everything he is doing, but has absolute control of all motions of the machine.

Ore bridges. The ore taken out of the boats is deposited in a huge concrete trough directly in the rear of the unloaders. From this point it is picked up by the ore bridges, of which there are five. These bridges are of the cantilever type, having a total over-all length of 459 ft. The lifting capacity of this bridge is 13 tons of ore, in addition to the weight of the bucket. The total weight of the bridge is 238,000 lb. The rear end of the bridge is considerably longer than is necessary to take ore out of the trough; the bridge was made this way so as to be used as a traveling crane for repairing the unloaders.

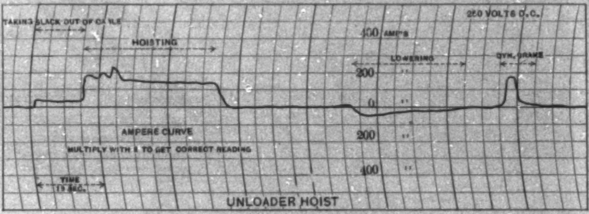


FIG. 13.—Chart showing the fluctuating load on the ore unloaders. To be read from right to left.

The motor equipment of the bridges is given in the following table. The trolley and hoist motions are controlled by automatic magnetic control. The secondary motions, which are seldom used, are controlled by hand. Fig. 14 and 15 represent clearly the character of load on the hoist and trolley motor of the bridge.

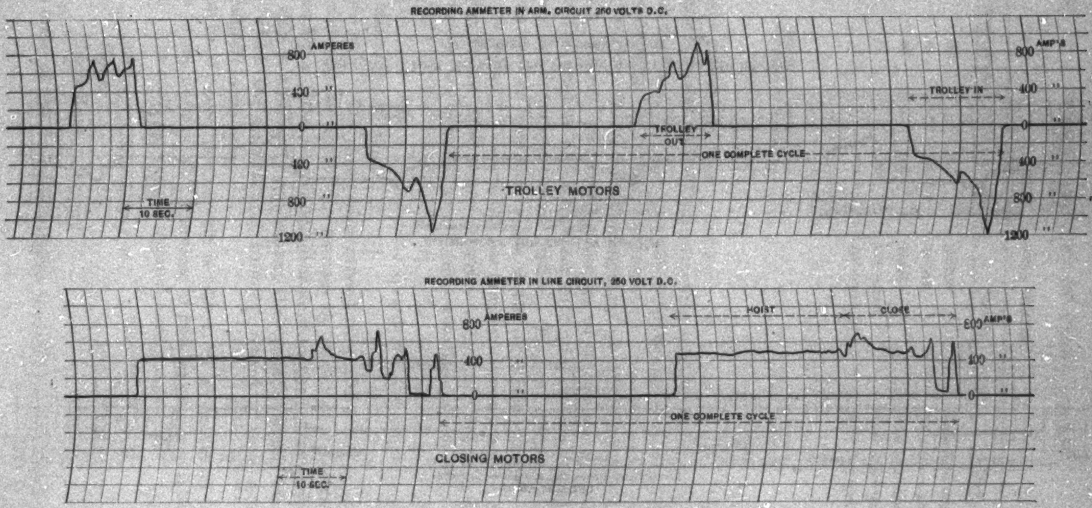


Fig. 14.—Charts showing the varying load on the ore bridges.
To be read from right to left.

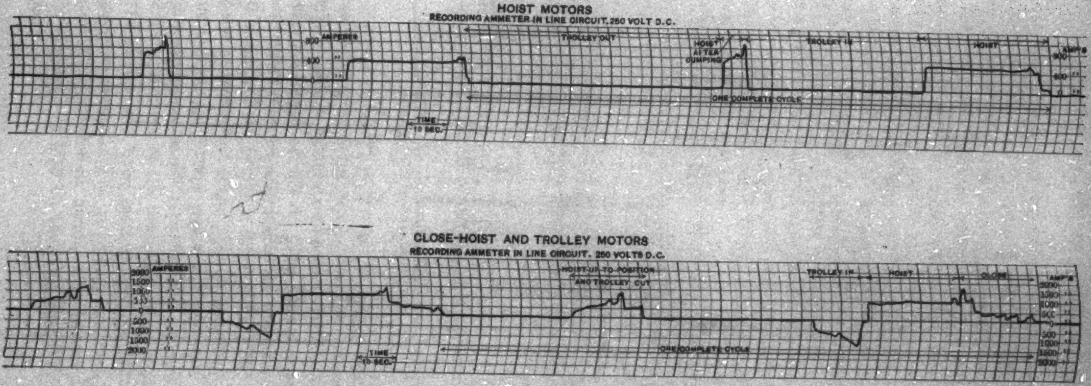


FIG. 15.—Chart showing the varying load on the ore bridges. To be read from right to left.

TABLE B.—ORE BRIDGE

	Horse power	Total horse power	Service	Type
4	30	120	Bridge	Series direct-current
4	40	160	Trolley	Series direct-current
4	80	320	Hoist	Series direct-current
1	10	10	Ore pocket	Shunt direct-current
1	8.5	8.5	Air compressor	Series direct-current
		Total h.p. 618.5		

Weight of bridge	238,000 lb.
Capacity of hopper	60,000 lb.
Total	298,000 lb.

Bins with transfer car. Between the order yard and the line of blast furnaces there is located a long steel trestle-like structure which contains the ore, coke, and limestone bins. The ore picked from stock by the bridge is deposited in a transfer car of 100,000 lb. capacity, the electrical equipment of which consists of two 50-h.p. motors operated by means of an ordinary street-car controller, and an air compresser supplying air for opening and closing the doors and for air brakes. This car is used for transferring the ore from the bridge to the appropriate bin.

Scale larries. Underneath the bins are the scale larries, driven by one 21-h.p. direct-current series motor, and carrying a similar motor for opening and closing the door of the bin. This larry is used for transferring ore, coke, and limestone from the various bins in the appropriate quantities and depositing it in the blast-furnace skip.

Skip cars. The material is carried from this stock house and dumped into the top of the furnace by means of a double skip, driven by a 150-h.p. compound-wound motor. The control of this skip is absolutely automatic; the operator simply starts it, after which the accelerating, running, retarding, and stopping are entirely automatic.

The total travel of this skip is 163 ft. up an incline at 60 degrees to the horizontal. The time of making one trip is 60 seconds. The loads carried are approximately as follows:

Ore	7000 lb.
Coke	3600 "
Limestone	6000 "

In spite of the variable weights carried this skip stops automatically within about 4 in. of the same place under all conditions. In the cast-house of each furnace is located a 15-ton crane for handling runners, scrap, etc.

Pig-casting machine. For taking care of the material from the blast furnaces on Sundays, when the open-hearth plant is not in operation, a pig-casting machine is provided. There is a main building in which are located two double-trolley ladle cranes; the main hoist is 75 tons, and the auxiliary hoist 15 tons. Six strings of moulds and conveyors are provided for disposing of the cast material. The ladle is handled by a 5-ton electrically operated jib-crane. The moulds are driven by 40-h.p., 750-rev. per min. induction motors and conveyed by 30-h.p., 750-rev. per min. induction motors.

Fig. 16.—Low type open-hearth charging machine.

Open hearths. Each open-hearth plant consists of fourteen 60-ton furnaces. The molten metal from the blast furnaces is poured into a 300-ton mixer by a 75-ton electric ladle crane of the same design as that in the pig-machine building.

The metal is carried from the mixer to a point in front of the various furnaces by an electrically operated hot-metal car whose equipment consists of two 25-h.p., 250-volt, 290-rev. per min. series motors, operated by a standard series-parallel controller. The ladle from this car is handled and the contents poured directly into the open-hearth furnaces by another 75-ton ladle crane.

The cold scrap for charging the furnace is stored and handled in the stock-yard, which is entirely covered by two 5-ton electric traveling cranes. The stock is handled by means of electro-magnets, each one capable of handling from 1000 lb. to 2000 lb. of scrap, according to the character of the material, or of lifting 10,000 lb. in large pieces. After this scrap is loaded, the charging boxes are shifted in front of the open-hearth furnaces and the contents put in by means of a low-type charging machine, as shown in Fig. 16. The equipment consists of: a main hoist, with a 30-h.p. series motor; bridge travel, two 30-h.p. series motors; trolley, 20-h.p. series motor; tilting, 11-h.p. series motor; rotate, 3.25-h.p. series motor.

The steel is handled in 60-ton ladles by three 125-ton ladle cranes. The electric equipment is as follows: main hoist, 110 h.p.; first auxiliary hoist, 50 h.p.; second auxiliary hoist, 30 h.p.; main trolley, 30 h.p.; auxiliary trolley, 11 h.p.; bridge travel, two 50-h.p. motors. The controllers for this apparatus, except that for the main hoist on all ladle cranes, (which is automatic magnetic control) are of the ordinary hand-operated lever type.

The electrical equipment of cranes, etc., in these open hearth plants is practically the same as that in common use at other plants.

The electric equipment of the coal-handling apparatus in connection with the gas producers for these furnaces consists of a coal crusher driven by a 25-h.p. direct-current motor; a double-skip coal elevator driven by a motor similar to that on the coal crusher; and four hopper cranes, each driven by 7.5-h.p. series motors. The hopper cranes are used for distributing crushed coal in overhead bins directly into the producers.

The control of the skip is entirely automatic in its action. As the descending car approaches the bottom point of its travel, it opens the door of the coal bin; in stopping it rests on a counter-weighted lever. When the skip is nearly filled with coal the counterweight on this lever is overbalanced, the skip dropping down about 3 in. more. This actuates the switch which starts the skip on its upward travel, its first action being to close the door of the coal bin. The operation is repeated by the second skip and continues, unless stopped, until the coal bin is entirely empty.

In connection with the open-hearth plant are two stripper buildings, one of which contains one, and the other, two, 200-ton electrically operated stripper cranes. These cranes are equipped with 100-h.p., 375-rev. per min. series motors on the main hoist; a duplicate to the above on the stripping hoist; 30-h.p., 500 rev. per min. trolley motors, and one 50-h.p. 480-rev. per min. motor on the bridge.

In the soaking pits are three 7.5-ton soaking-pit or ingot cranes. Each of these cranes has a 5-ton, high-speed auxiliary hoist on the trolley for repairing the pits. The electrical equipment is as follows: main hoist, 50 h.p.; auxiliary hoist, 30 h.p.; trolley, 7.5 h.p.; bridge, two 50 h.p.; tongs, turning and opening, 5 h.p.

FIG. 17.—Control pulpits for rail mill.

For delivering the ingots from the pit to the first table in the rolling mill two ingot buggies are used, for which a special control has been designed. Each buggy is intended to take care of six rows of four pits which are located respectively north and south of the table. To prevent the two buggies colliding, should both happen to be coming toward the table at the same time, the trolley bars, through which the current is transmitted to the motors on the buggies, are in three sections, one section in front of the table and one long section on each end

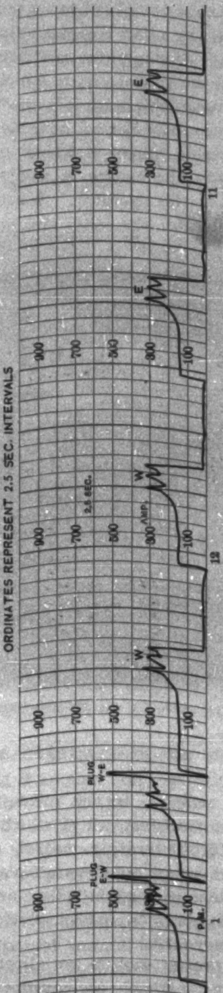


FIG. 18.—Chart showing current variation on two 25-h.p. motors, operating in parallel on the same shaft, driving a mill table. To be read from right to left.

of the first section. Each controller has six points corresponding to the six rows of pits, one point corresponding to the table and one to the off position. The operator can throw his controller to the point representing the row of pits to which he desires to run, and when the buggy reaches this point it is automatically stopped. Return motion with the controller on the table position will bring the buggy up to the table, where, however, on account of the great accuracy required, the buggy is not stopped automatically but at the will of the operator. When one buggy is at the table it is impossible for the other one to reach that point, as the two controllers are so interlocked as to prevent this occurrence.

FIG. 19.—Lifting table for the 40-inch blooming mill.

Table and transfer motors. In the rolling mill proper there are 21 tables and two transfers, all of which are controlled by automatic magnetic torque-limiting control.

The eight operators stand on elevated platforms or pulpits, shown in Fig. 17. Some of the controllers are mounted on the operating pulpits and others on special platforms located near the motors which they control.

These tables and transfer motors are all of the so-called mill type. Tables running constantly are equipped with series-shunt motors. Those doing a considerable amount of reversing or frequent starting and stopping have series-wound motors. Fig. 18 gives the ampere chart of one of these tables.

The transfers have a simple chain drive, having two sets of dogs for moving the rail sidewise, and the control is entirely automatic. When the operator throws his controller to the forward position, the transfer chain makes one-half revolution, depositing the rail in the proper place. Then the motor stops automatically. The next motion, for transferring the following rail, is made by the operator putting his controller to the "off" position and again throwing it to the "on" position.

FIG. 20.—Lifting table for the 40-inch blooming mill.

An interesting feature of the auxiliary drive is that of the lifting table at the three-high 40-in. blooming mill, Fig. 19, 20 and 21. This table has a total weight of 256,000 lb., partly counterbalanced by means of a cylinder containing air at 500 lb. per square inch pressure, and is lifted or lowered 40 in. in 3 sec. The operating motor is 250-h.p. 250-volt direct-current, 100-rev. per min. compound wound. The control, like that of the table motors, is entirely automatic and is manipulated by the operator simply throwing his master controller to the up or down position, the accelerating, running, retarding, and stopping being taken care of automatically.

There is also a tilting table at the three-high roughing rolls similar to the lifting table, but of considerably less weight. This table gives one complete stroke of 26 in. either up or down in 1.5 sec. It is driven by a 150-h.p., 250-volt, 100-rev. per min., compound-wound motor and is controlled like the lifting table.

Fig. 21.—Lifting table for the-40-inch blooming mill.

The hot saws, Fig. 23, five in number, are driven individually by 40-h.p., 750-rev. per min. induction motors. The saws are 40 in. in diameter and make 1440 rev. per min. All five are raised and lowered at one time by a crank shaft, operated by a 25-h.p. series shunt-wound mill-type motor. The control is similar to that of the lifting table, except that if the operator throws his control to the first point the saws lower and stop in that position. It is then necessary for him to bring his control to the first point on the reverse in order to raise the saws; then the latter come up to the top and again stop automatically. In regular operation, however, the operator throws to the second point; upon which the saws lower, cut the rail and again rise, stopping automatically in the upper position.

The cambering machine is driven by a 40-h.p., 750-rev. per min. induction motor. On the hot beds, four in number, there is a push-up for shoving the rails off the delivery table onto the beds, and a pull-up for dragging the rails from the beds onto the receiving table in the finishing mill. These "push-ups" and "pull-ups" are driven by 75-h.p. series mill-type motors, the controllers of which are also automatic.

From the receiving table the rails are delivered in both directions to the finishing department by feed tables similar to those in the rail mill. Because of the continuous running of these feed tables the controllers are the ordinary hand-operated type.

For delivering the rails from this table to the straightening beds "kick-offs" are used. These are simply bars lying normally below the surface of the table but raised at an angle so that rails are lifted and then slid off by means of a cam on a motor-operated shaft. The straightening presses 18 in number, are driven by 10-h.p., 750-rev. per min. high-resistance-rotor induction motors. Opposite the ends of the straightening beds for each straightening press is located a 24-in. headlight in which is used an ordinary 16-c.p. lamp to enable the straightener to see his rail clearly.

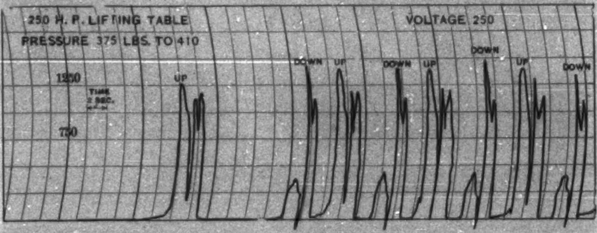


FIG. 22.—Chart showing load on lifting table.—To be read from right to left.

The drill presses, 18 in number, are driven by 10-h.p., 750-rev. per min. induction motors with ordinary squirrel-cage rotors.

All the induction motors in the finishing department are standard and are controlled by means of a triple-pole, double-throw switch which is connected to a five-wire system. The two extra wires are taps taken off the main transformers, thus furnishing low voltage for starting. This system does away entirely with the complication and trouble accompanying individual starting compensators.

The loading beds outside are covered by two special electric cranes which transfer the rails from one part to the other or load them in cars, the rails being handled by means of large special magnets.

On the south side of the runway of these cranes is also a small monorail crane, whose sole purpose is to deliver rails to the cold-saw bed.

FIG. 23.—The hot saws.

The cold saw, a tooth saw 42 in. in diameter making 1800 rev. per min., is driven by a 100-h.p., 750-rev. per min. induction motor. This saw is capable of cutting an 85-lb. rail in 22 seconds, the load varying between 50 and 100 h.p. according to the part of the rail that is being cut.

Motors for driving the rolls. As outlined earlier in the paper, although electric motors have been used for some time to drive rolls, the motors used in this plant are several times larger than any motors of their type previously built. Their use for this purpose marks a new era in the industrial application of electric power, and a short description of some of the principal eatures in the design of these motors is not out of place.

Horse power:					
Normal continuous rating 40° cent rise	2000	2000	6000	6000	6000
25% overload continuous 50° cent. rise	2500	2500	7500	7500	7500
50% overload for 1 hr. 60° cent. rise	3000	3000	9000	9000	9000
Speed:					
Synchronous	214	68	83.3	88	75
Full load					
Maximum slip, %					
Performance specification number					
Outline drawing number					
Bearings:					
FLYWHEEL SIDE.					
Diameter	24	26	30	30	30
Length	60	65	70	70	70
COLLECTOR SIDE.					
Diameter	24	26	30	30	30
Length	60	65	70	70	70
Thrust collar area	575	910	1370	1370	1370
Revolving part of motor:					
Diameter	8 ft. 8 in.	21 ft. 0 in.	21 ft. 0 in.	21 ft. 0 in.	21 ft. 0 in.
Flywheel effect, lb. at 1 ft. radius	354,000	8,950,000	11,600,000	11,600,000	14,100,000
Stationary part of motor:					
Outside diam. of frame	13 ft. 4 in.	28 ft. 0 in.	28 ft. 0 in.	28 ft. 0 in.	28 ft. 0 in.
Width of frame	3 ft. 10 in.	3 ft. 8 in.	4 ft. 11 in.	4 ft. 11 in.	4 ft. 11 in.
Air-gap, total	0.28	0.40	0.40	0.40	0.40
Induction motor:					
Poles	14	36	44	34	40
Horse power	2000	2000	6000	6000	6000
Rev. per min	214	68	83	88	75
Volts	6600	6600	6600	6600	6600
Efficiency at full load	95%	93%	95.5%	95.5%	95.5%
Power factor at full load	89%	80%	87%	88%	88%
Break-down torque	6,800h.p.	5,100h.p.	18,500h.p.	20,600h.p.	16,400h.p.
Flywheel:					
Material	Laminated steel		—	—	—
Number of sections					
Diameter	17 ft.	—	—	—	—
Outline dimensions:					
Height of machine above bottom of base	12 ft. 2 in.	21 ft. 0 in.	21 ft. 0 in	21 ft. 0 in.	21 ft. 0 in.
Width of bed plate	20 ft. 4 in.	32 ft. 8 in.	32 ft. 8 in.	32 ft. 8 in.	32 ft. 8 in.
Length of bed plate	20 ft. 2 in.	18ft 11½in	21 ft. 9 in.	21 ft. 9 in.	21 ft. 9 in.
Total length of shaft	22 ft.4¾in.	21 ft.3¾in.	24 ft.6¾in.	24 ft.6¾in.	24 ft.6¾in.
Center line of shaft to bottom of base.	5 ft. 6 in.	7 ft. 0 in.	7 ft. 0 in.	7 ft. 0 in.	7 ft. 0 in.
Weights:					
Stationary part of motor	42,500	126,000	175,000	175,000	175,000
Rotating part of motor without shaft	30,800	148,000	176,000	176,000	209,000
Shaft (hollow)	33,400	34,300	50,000	50,000	50,000
Pillow-blocks with bearings	72,300	105,500	138,000	138,000	138,000
Bedplate	100,000	150,000	185,500	185,500	185,500
Flywheel	100,000	—	—	—	—
TOTAL.					
Without flywheel	296,000	—	—	—	—
Complete	396,000	578,000	749,000	749,000	783,000

FIG. 24

The main rolls of the mill are driven by six induction motors having a combined capacity of 24,000 h.p. made up of the following units:

Two	2000 h.p. at	214	rev. per min.
One	2000 h.p. at	68	"
One	6000 h.p. at	88	"
One	6000 h.p. at	83	"
One	6000 h.p. at	75	"

In the construction of these motors the parts were made extremely heavy and rigid, following out as far as possible the practice which has proved successful in the construction of steam engines for similar duty. The stator frame is of the box-type construction, and is split into four sections for ease in handling and transportation. The rotor spider is of cast steel and is made up of four sections with two arms per section. The sections are bolted to disc hubs which are pressed on the shaft.

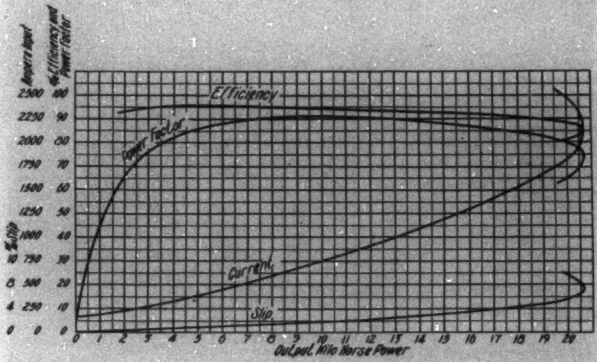


FIG. 25.—Characteristic curves of the 6000-h.p., 88 rev. per min. induction motor.

As the flywheel effect of the rotors necessary to overcome the excessive loads in rolling can only be determined accurately by actual trial, it was deemed advisable where possible to construct the motors so that the flywheel effect could be altered after the motors had been put in operation. This was accomplished in the 6000-h.p. and the 2000-h.p. motors at 68 rev. per min.

by attaching to the rotor spiders heavy cast-steel rims which could easily be removed and exchanged for rims of different weights.

On account of their high speed the two 2000-h.p., 214-rev. per min. motors have separate flywheels weighing 100,000 lb. each. These flywheels are built up of riveted boiler plates, which do not permit of alteration.

The end-thrust which may result from a diagonal fracture of a spindle or roll is frequently sufficient to wreck either the mill or the motor unless special precautions are taken. This problem, which is extremely difficult to solve when an engine is used for driving the rolls. is very easily solved when electric motors are used. A device termed a mechanical fuse is attached to the pedestal by two breakable rods These rods are so proportional that they will break only when the end-thrust exceeds 150 tons. When the rods give way under this pressure, the rotor is free to move longitudinally away from the rolls, thereby relieving the thrust. To prevent injury to the brush rigging, it is so arranged as to move freely with the brushes, always maintaining their proper position on the collector rings.

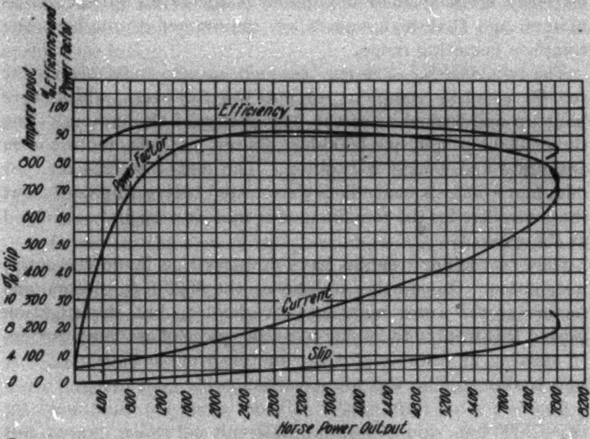


FIG. 26.—Characteristic curves of the 2000-h.p. 214-rev. per min. induction motor.

The bearings are self-aligning, with oil-ring lubrication.

They can also be lubricated from an independent oiling system. Provision is made for water cooling in case of emergency.

The coils, which are assembled in open slots, are very rigid. In order, however, to prevent any possible vibration due to excessive fluctuations of the current, the coils are also firmly laced to a rigid supporting ring.

The electrical characteristics of the motors are shown by Fig. 25 and 26, which represent the results of tests of the 2000-h.p. motor at 214 rev. per min. and the 6000-h.p. motor at 88 rev. per min.

Reference to these curves shows that the power-factor and efficiency are near their maximum at the rated output of the motors, and that high values are maintained throughout the complete operating range.

The two 2000-h.p. 214-rev. per min. motors were received at the Gary works complete, except the flywheels which were built up and turned after the installation of the motors. The three 6000-h.p. and one 2000-h.p., 68-rev. per min. motors were assembled and wound in position. The 2000-h.p., 214-rev. per min. motor and its controllers were tested before shipment, but the controllers for the remaining four motors were first assembled at the works.

Only two minor troubles have developed so far in the entire installation. On starting up one of the 6000-h.p. motors, one section of the rotor resistance overheated, but investigation proved this trouble to be due to a stray piece of arc-lamp carbon. In starting up another of these motors trouble developed due to a broken grid in the rotor resistance.

Control for roll-train motors. In designing the equipment for these 2000-h.p., and 6000-h.p., 6600-volt induction motors, not only were the sizes of the motors to be controlled beyond anything previously attempted, but the specifications presented many novel features.

For most of the motors the service required a very large flywheel effect. Because of the well-known characteristics of the induction motor, it was clearly recognized that there would necessarily be large fluctuations in current, even though the flywheels were very large, unless some means were employed for automatically introducing resistance into the motor circuit whenever the load was sufficient to cause even as small a change of speed as two or three per cent. It was desirable that the automatic features be adjusted so as to operate continuously, regulating the current taken by the motors so that the demands on the source of supply for any one motor would be uniform—the motor and its flywheel, meanwhile, accelerating and decelerating at a point just below synchronism to meet the power demands of the rail mill which it was driving.

The large current in the secondary circuits of the motors necessitated separate contactors. Rheostats were arranged in multiple delta, and the successive value of the resistance was made such that as each contactor closed, the rush of current through it would be approximately one-fourth of the intake of the motor. This arrangement prevents the rheostats or contactors being called upon to carry anywhere near their full rated current, and gives the whole control system a conservative continuous rating.

The control apparatus for each motor consists of:

A. Preliminary control apparatus, which includes the oil switches, reversing switches, series transformers, primary relays, etc.

B. Secondary control, comprising the rheostats, contactors, regulating panel, etc.

C. Master controller.

Reference to the plan of the plant shows that the motors and the controlling apparatus are placed in a room separated from the rolling mill proper by a partition. The master controller, however, is in the rolling mill. Under these conditions, therefore, the operator must depend chiefly on the automatic features of the control, which are so far away that he must judge of their correct working by the behavior of the rolls while the steel is passing through them. In case of emergency provision is made for the motor attendant to shut down the motors independently of the master controller.

The 6600-volt circuit enters through the triple-pole main oil-switch; thence it passes through a number of oil-switches which determine the direction of rotation. These switches are interlocked, making it impossible for them to be operated unless the main switch is open. Additional interlocks prevent them from being closed simultaneously.

This group of preliminary-control apparatus also includes the necessary relays to open the circuit in case of overload and to prevent the secondary control from being operated in an injurious manner.

The arrangement of the secondary-control rheostats in multiple delta is shown in Fig. 30. Direct current at 250 volts was adopted for the control of this secondary apparatus, and the voltages were so arranged that each contactor coil is subjected to a pressure of only about 15 volts. This pressure is so small that the arcing is insignificant. To compensate for the different number of contactors in circuit at different speeds, a balancing resistance equaling the resistance of the contactor is cut in or out of circuit inversely as the contactor. This keeps the current in the contactor circuit approximately constant at about 5 amperes, and results in a simple arrangement of contacts on the regulating device. The regulating device consists of two concentric groups of buttons, one connected to the contactor coils and the other group to the contactor resistances, the two groups being cross-connected, step by step, by a simple arm controlled automatically. Should the 250-volt supply fail, a weight attached to the grooved pulley on this arm serves to return the mechanism to the off position. The master controller which operates both the preliminary-control and secondary-control apparatus has two handles; one is a reversing handle, and the other is for applying and shutting off the power.

FIG. 27.—The 2000-h.p., 214-rev. per min. induction motor, which drives passes 1, 2, 3, and 4.

The rail mill. The rail mill has a capacity of 4000 tons of finished rails per 24 hours. It is not only the largest, but also the only motor-driven mill in the world rolling rails directly from the ingot without reheating.

There are nine passes in the blooming mill. The first two passes are two-high rolls of 42 in. pitch diameter running at 6 rev. per min., and are connected to one of the 2000-h.p., 214-rev. per min. motors through gear reductions. The next two passes are identical with passes one and two, except that the rolls are 40 in. in diameter and make 10 rev. per min. and are driven in the same manner. The next five passes are made in a 40-in. three-high train direct-connected to a 6000-h.p., 75-rev. per min. motor. The lifting table for this train has already been described.

FIG. 28.—The 6000-h.p., 75-rev. per min. induction motor, which drives passes, 5, 6, 7, 8, and 9.

The bloom as delivered from pass 9 is then cut in two by means of the bloom shears, operated by a 75-h.p. induction motor.

The next train of rolls, which comprises a three-high roughing mill with passes 10, 11 and 12, is operated by means of the tilting table, the second edger or pass 16 and leader or pass 17. This train is 28-in., pitch diameter and direct-connected to a 6000-h.p. motor running at 83⅓ rev. per min.

The next pass is the 28-in. two-high former, direct-connected to a 2000-h.p., 68-rev. per min. motor.

The third roll train consists of the dummy, or pass 14; the first edger, or pass 15, and the finisher, or pass 18. These rolls also are of 28-in. pitch diameter and the train is direct-connected to a 6000-h.p. 88-rev. per min. motor.

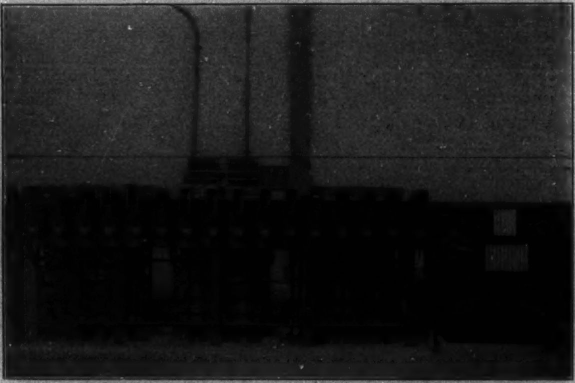


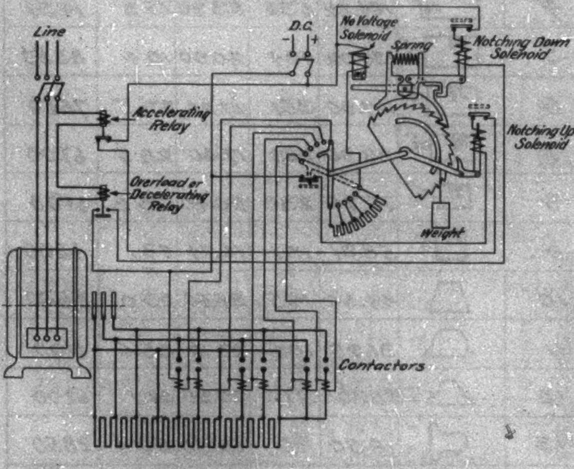
Fig. 29.—Secondary control for the 6000 h.p., 75-rev. per min. motor.

A diagram of these passes, together with the approximate shapes of the pieces leaving them, is shown in Fig. 31 and 32, the former also showing the table giving the size of the pieces leaving the various passes, the area in square inches, the weight per linear foot, percentage of reduction, length of piece, and horse power per pass—all as observed in the rolling of the first rail, which was an 80-lb., 33-ft. rail.

To supply power to the train motors of this mill there are two circuits, each of 10,000-kw. normal capacity at 6600 volts. One circuit feeds the three blooming-mill motors; that is, two 2000-h.p. and one 6000-h.p. The other circuit feeds the other three motors; that is, two 6000-h.p. and one 2000-h.p.

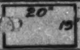
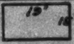
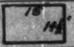
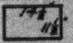
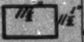
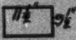
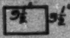
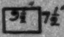
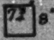
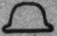
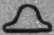
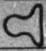
The estimated combined load with the mill working at full capacity, with voltage and amperage of each of the circuits, is shown in Fig. 33.

In originally designing the mill careful calculations were made of the time and horse power required to operate each pass. These data, with the calculated interval between passes, are shown clearly in Fig. 35. It will be noted on the right-hand side of this curve that there are both solid and dotted areas. The dotted area represents the second piece of the ingot after it had been cut at the bloom shears between passes 9 and 10, and the load estimated with the second piece in pass 10, while the first piece is yet in pass 12. Though it is improbable that such conditions will exist except in cases of the most rapid rolling, it was thought advisable to use them in the calculations of the mill. These calculations determined not only the total time consumed by the ingot from start to finish, but also the shortest possible time between ingots, the limiting time being in the three-high roughing mill.


Line
D.C.
- +
No Voltage Solenoid
Spring
Notching Down Solenoid
Accelerating Relay
Notching Up Solenoid
Overload or Decelerating Relay
Weight
Contactors

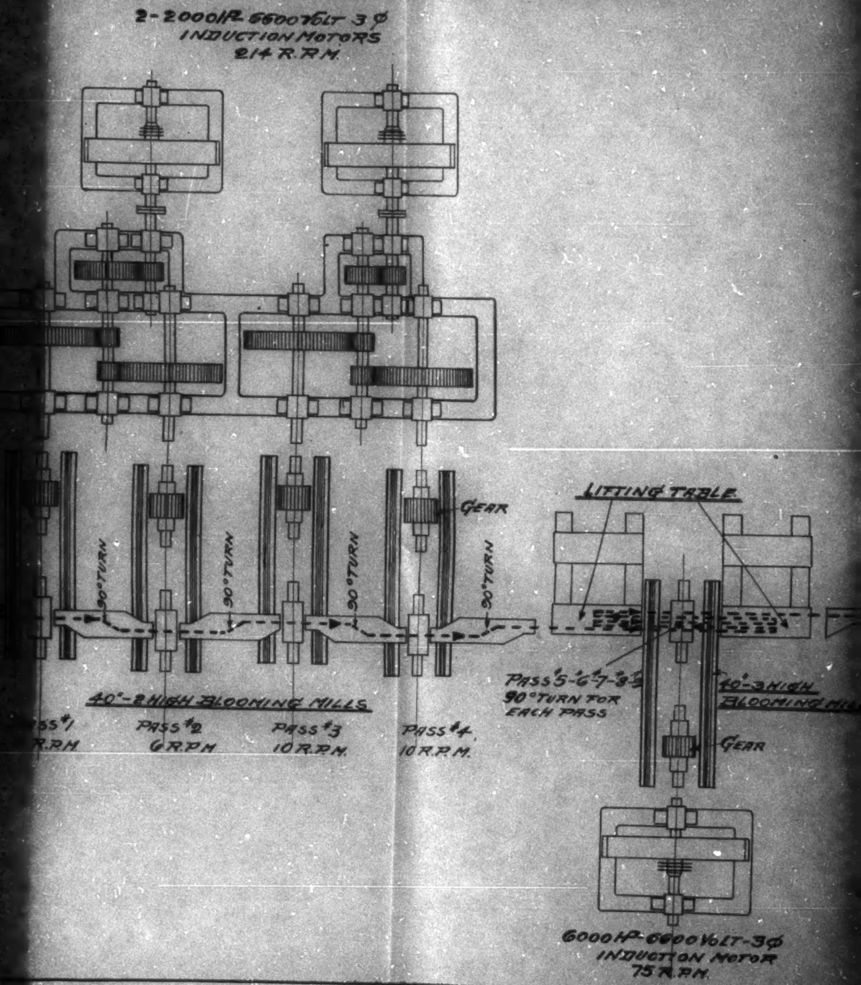
Simplified Control Connections for 6000 H.P. Induction Motor.

FIG. 30.—Diagram of secondary control of the rail-mill motors.

PASSES	SIZE OUT	AREA OUT	WEIGHT PER FOOT	% RED.	LENGTH OF PIECE	HP ON ROLLS
1		376.56	1224	21.20	6.7	1000
2		282.37	918	25.00	9.0	1260
3		214.87	698	23.90	11.8	1600
4		164.82	536	23.30	15.3	14.50
5		130.32	424	20.90	19.4	8350
6		107.90	351	17.20	23.5	7650
7		88.90	289	17.60	28.5	6700
8		70.76	230	20.40	35.8	6100
9		58.91	191	16.74	43.1	4500
10		44.50	145	24.40	25.0	5500
11		31.25	102	29.10	35.6	5100
12		21.80	71	29.90	51.1	6200
13		18.50	60	15.50	60.4	2850
14		16.00	52	13.50	69.7	5650
15		12.80	42	20.00	86.3	
16		10.07	33	21.33	100.0	1500
17		8.62	28	14.40	130.5	980
18	RAIL	8.095	26.6	6.09	137.87	720

NOTE: TABLE FOR 80 lbs 33'-0" RAILS.
INGOT BUTT 20" x 24"
TOP 18¾" x 22¾" - 65½" WT. 8256 lbs

FIG. 31


2-2000 HP 6600 VOLT 3 φ
INDUCTION MOTORS
214 R.P.M.
90° TURN
90° TURN
90° TURN
90° TURN
GEAR
LIFTING TABLE
40"-2 HIGH BLOOMING MILLS
SS #1
R.P.M
PASS #2
6 R.P.M
PASS #3
10 R.P.M.
PASS #4
10 R.P.M.
PASS #5-6-7-8
90° TURN FOR
EACH PASS
40"-3 HIGH
BLOOMING MIL
GEAR
6000 HP-6600 VOLT-3φ
INDUCTION MOTOR
75 R.P.M.

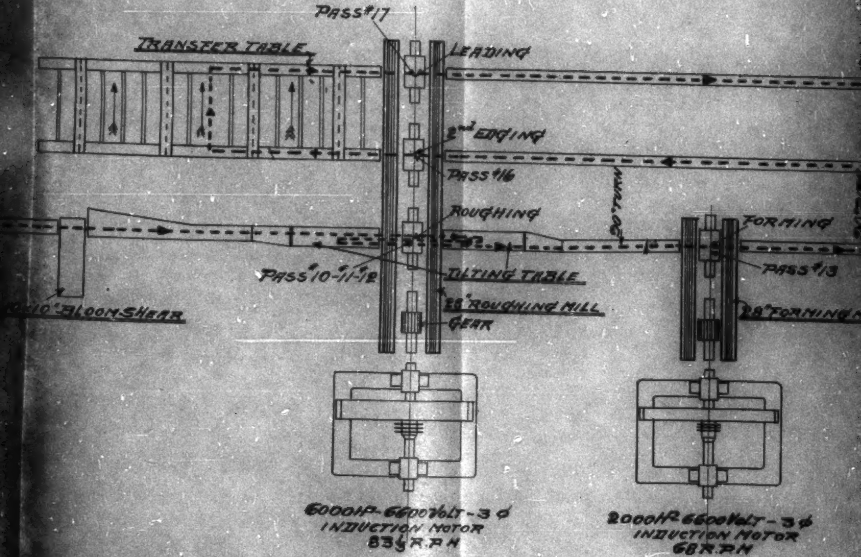
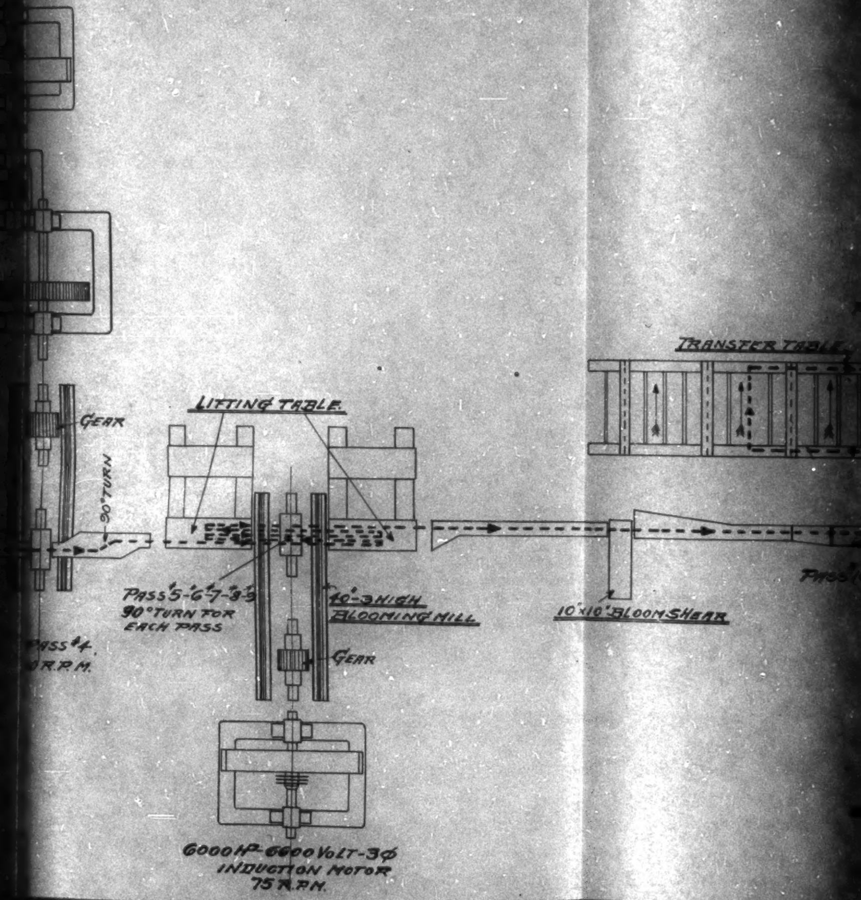
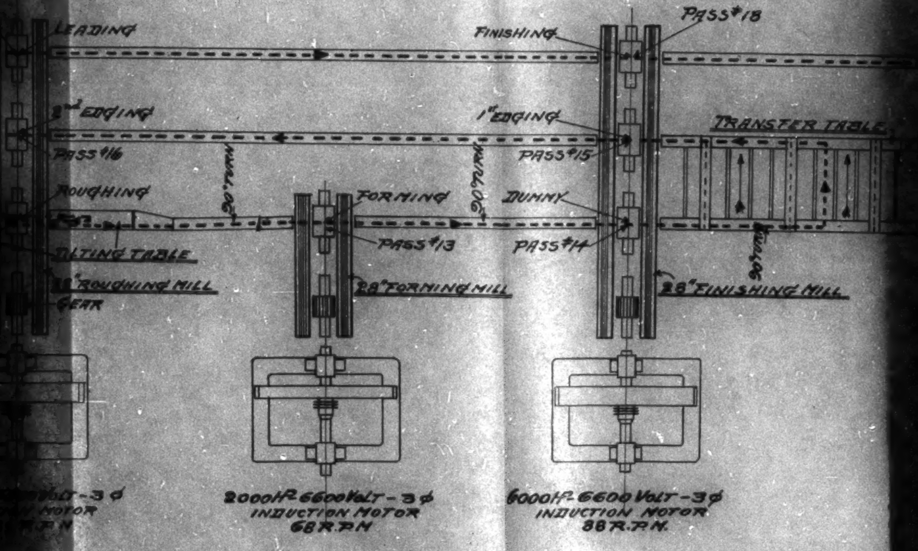

PASS#17
TRANSFER TABLE
LEADING
2nd EDGING
PASS#16
ROUGHING
FORMING
PASS#10-11-12
TILTING TABLE
PASS#13
x10" BLOOM SHEAR
28" ROUGHING MILL
28" FORMING
GEAR
6000 HP-6600 VOLT-3 φ
INDUCTION MOTOR
83⅓ R.P.M
2000 HP 6600 VOLT-3 φ
INDUCTION MOTOR
68 R.P.M

Fig. 32.—Plan of the rail mill


TRANSFER TABLE
LIFTING TABLE.
GEAR
90° TURN
PASS #5-#6-#7-#8-#9
90° TURN FOR
EACH PASS
40"-3 HIGH
BLOOMING MILL
10"x10" BLOOM SHEAR
PASS #4.
0 R.P.M.
PASS 1
GEAR
6000 HP-6600 VOLT-3φ
INDUCTION MOTOR
75 R.P.M.



LEADING
2nd EDGING
PASS #16
ROUGHING
TILTING TABLE
28" ROUGHING MILL
GEAR
VOLT - 3 φ
MOTOR
FORMING
PASS #13
28" FORMING MILL
30' TURN
90' TURN
FINISHING
PASS #18
1st EDGING
PASS #15
DUMMY
PASS #14
TRANSFER TABLE
90' TURN
28" FINISHING MILL
2000 HP 6600 VOLT - 3 φ
INDUCTION MOTOR
68 R.P.M
6000 HP 6600 VOLT - 3 φ
INDUCTION MOTOR
88 R.P.M.

of the rail mill

These curves were then superimposed on each other at this interval, which was 31.89 sec., until the number of ingots was increased to the maximum load on the mill. Adding the ordinates under this condition Fig. 34 was produced, showing the integrated load carried by the motors. The shaded portion indicates motor and line losses. and the upper line of the curve shows the character of the load on the power station.

This cycle, which is 31.89 sec. indicates an exceedingly variable load, the total variations being from a minimum of 4300 h.p. to a maximum of 19,010 h.p. with an average of 12,025 h.p., which makes the load-factor on the six-train motors almost exactly 50 per cent. The curve was developed to provide a basis for estimating the size of the storage-battery necessary to take care of the fluctuations and keep a constant load on the generating station.

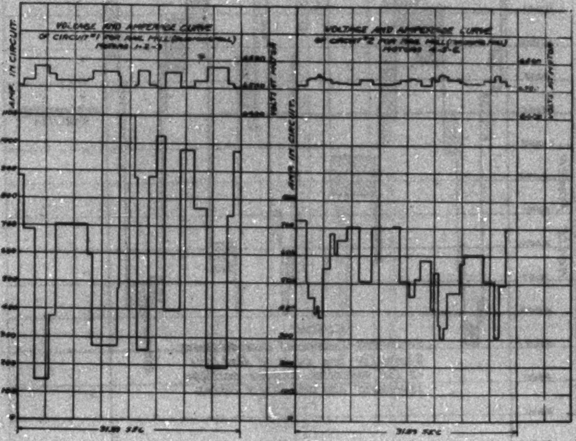


FIG. 33
To be read from left to right.

Conclusions. One of the most satisfactory conclusions, so far as the Indiana Steel Co. is concerned, that can be drawn at the present date is that so far all the apparatus described in this paper, which has been tried out, has been practically a perfect success. Nothing has occurred to indicate that there is any necessity of changing anything to a radical extent. As an example of this, the ore-handling machinery was started on

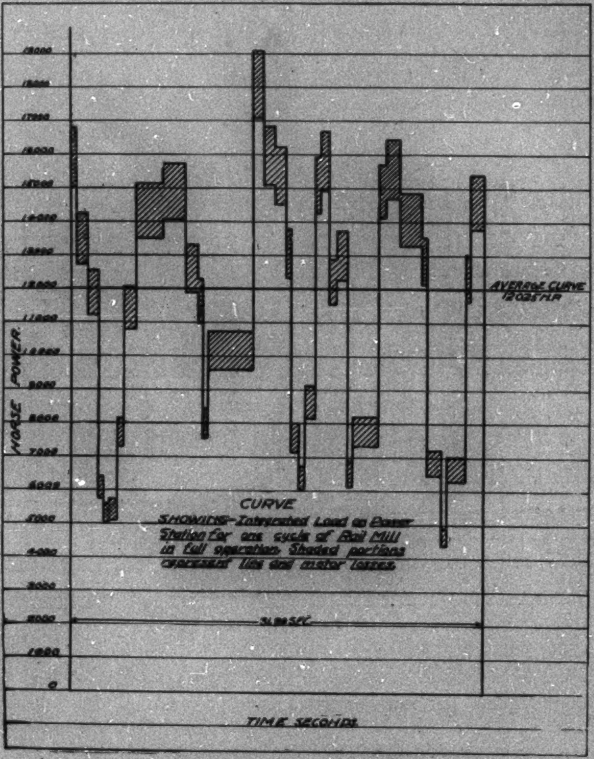


FIG 34.—Chart showing estimated combined load on the mill. To be read from left to right.

July 23, 1908, and by Nov. 1, three-quarters of a million tons of ore were stored in the yard, with virtually no more trouble from the machinery than would have been experienced at a works which had been in operation for several years.

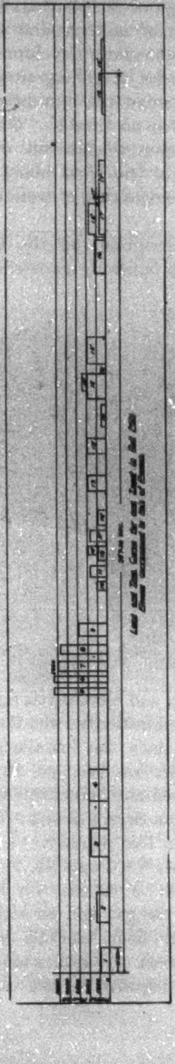


FIG. 35.—Chart showing calculated time and horse power per pass.

In the original design of the plant considerable attention was given to the question of underground versus overhead transmission. In view of some later developments although it might have been possible to put in underground service, which would not have greatly exceeded the cost of overhead construction, yet the latter has given no trouble. On the night of Jan. 29, during one of the severest wind storms ever experienced in this section, the velocity of the wind being estimated at over 70 miles per hour, not a single case of trouble occurred on the lines within the plant.

As stated in the description, all the 6600-volt feeders were protected by multigap lightning-arresters, while the 22,000-volt line has both multigap and electrolytic lightning-arresters. The latter were not installed until after the former had been operated for some time, and since the installation of the electrolytic lightning-arresters there has been no discharge over the multigap, nor have there been any bad effects from lightning either in the plant of the Indiana Steel Co. or at other points on the line, which are protected in like manner.

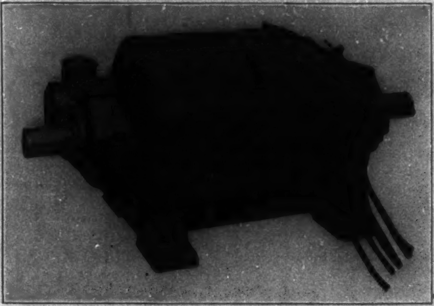


Fig. 36.—Mill type induction motor.

In open-hearth plants No. 1 and No. 2 one feature not adopted in No. 3 and No. 4 will be the use of a large number of electric motors for operating the gas and air valves and furnace doors which had previously been worked by hydraulic pressure.

A comparison between the estimated horse power and the observed horse power required for the various passes in the rail mill shows some discrepancy; but because the steel rolled was colder than it would have been in actual practice, since all of the machinery is new and is not operating so quickly as it should, and because also of the lack of adjustment of rolls, it is believed that the power required will be very little, if any, in excess of the original calculations. After the roll-train motors had been started it was discovered that the stopping of them was an important feature. The 2000-h.p., 214-rev. per min. motor when disconnected from the rolls required 2 hr. to come to rest, while the 6000-h.p., 83⅓ rev. per min. motor required 1 hr. and 37 min. to stop. This time consumed would mean corresponding delays in case of breaking of the main spindle, which, of course could not be countenanced. In order to stop these motors within a reasonable length of time, direct current at 250 volts was introduced into one phase of the winding through an external resistance after the motor had been disconnected from the 6600-volt line. By this device the 2000-h.p., 214-rev. per min. motor was stopped in 2 min. and 55 sec., and the 6000-h.p. motor in 1 min. and 42 sec. During this time the first section only of the resist-

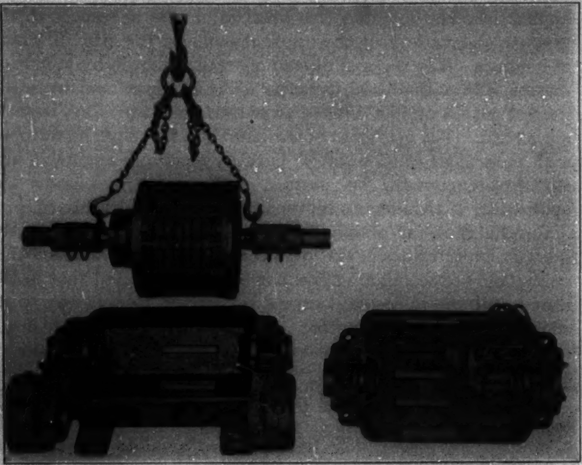


FIG. 37.—Disassembled view of mill-type induction motor.

ance of the rotor was closed. This device is being put in permanently, and a 6600-volt switch connected to one phase, the other side of which will be connected to the 250-volt line through a permanent resistance, and this switch interlocked with the main 6600-volt oil-switch so that both cannot be thrown in at the same time.

Probably no industrial application of electricity has been the result of more careful study on the part of the engineers in charge, or has marked a more general adoption of electric power than the one just described. Although many of the motor applications are not new, this plant is unique in respect to the number and variety of the applications and the size of many of its units. The rail mill now in operation, driven by induction motors with a combined capacity of 24,000 h.p., and having a normal output of 4000 tons of steel rails per 24-hr. day, is without a rival. The operation of the plant will therefore be watched with more than usual interest, both by steel-mill engineers and electrical engineers. Its success will greatly accelerate the application of the electric motor in this industrial field.

Results thus far obtained indicate that not only have the greatest expectations of the engineers been realized, but another stronghold of the steam engine has been carried, and that in the near future the rolling-mill engine is destined to give way to its successor—the electric motor.

DISCUSSION ON "THE INDUSTRIAL APPLICATION OF THE ELECTRIC MOTOR, AS ILLUSTRATED IN THE GARY PLANT OF THE INDIANA STEEL COMPANY." NEW YORK, MARCH 12, 1909.

B. A. Behrend: The subject of Mr. Shover's paper is not altogether confined to its title. Not only has he referred to the application of the electric motor in steel mills, but he has also described the usefulness of the storage battery in connection with steel mill problems. The application of blast-furnace gas in the power plant at Gary has also been mentioned. It is carried out there on the most gigantic scale. As the paper itself does not rigidly conform to its title, I wish to make a few remarks concerning the gas-engine generating plant which is illustrated in Fig. 3 and 4.

As the designer of the 17 generators constituting the 40,000-kw. gas-engine power plant at Gary, I have been particularly interested in the paper, and I wish to take this opportunity to add a few words regarding some special problems which arose in connection with the generating plant, which will contribute to a better understanding of the fundamental conditions which must be met in power plants utilizing alternating-current generators for direct connection to gas engines, a problem of the greatest importance in steel mills. The choice of the right flywheel effect is intimately bound up with this question, as the necessary moment of inertia of the flywheel can be determined intelligently only by the designer of the alternating-current generators.

The gas-engine power plant at Gary consists of 17 four-cycle, double-acting, cross-tandem gas-engine units of 2500-kw. capacity each. Two of these engines, No. 1 and 2, are direct-connected to two 2000-kw., 250-volt, direct-current generators, while the remaining 15 engines are direct-connected to alternating-current generators of 3000 kilovolt-amperes each at 6600 volts and 25 cycles. The engine speed is 83⅓ rev. per min.

As the load on this power plant is composed chiefly of induction motors of large capacity and slow speed, the amount of lagging current under average operating conditions is likely to be equal to, or even greater than, the amount of watt current required by the motors. The power-factor in this plant is not likely to exceed 70 per cent, and the generators, therefore, were designed for a large ampere rating at low power-factor.

Electric gas-engine-driven units must operate successfully in parallel if the gas engine is to be an important factor in steel mills. This problem resolves itself into an investigation of the periodic disturbing forces, produced by the engine, and the natural frequency of the generating unit. The periods of the former depend upon the type of engine used, if we neglect the period of the governor. As the gas engines at Gary are four-cycle double-acting, cross-tandem engines, there are introduced two periodic disturbing forces, due to inequalities in the force of explosions, adjustment of valve gear, leakages, etc., the frequencies of these forces being one per revolution, and one-half per revolution, of the engine. It is the latter frequency which is absent in steam engines, and which introduces a complex factor of the greatest importance into the problem of parallel operation of gas engines.

Following the terminology used in dynamics, we call the results of these periodic disturbing forces, " forced oscillations." For the Gary units the frequencies of the forced oscillations, which are likely to be dangerous, are 1.39 and 0.695 cycles per second.

It was shown by André Blondel and Boucherot in 1893, that synchronous generators and motors, when displaced from a condition of equilibrium, perform a series of swings which constitute the " natural frequency " of the oscillation of the generator or motor, and which can be dampened out just like other natural oscillations. The damping circuits in and between the pole faces, which were suggested at the time by Maurice Leblanc, perform this function.

The determination of the natural frequency by calculation, as carried out by Blondel, Boucherot, and Kapp, ten years ago, was based on a knowledge of the angular displacement of the revolving field per unit torque. The short-circuit current was used for this determination, but experimental investigations which I carried out with my former assistant, Mr. A. B. Field, have demonstrated that other methods must be resorted to if serious error is to be avoided.

Supposing that we know the natural frequency of the generating units when operating on bus-bars of constant frequency, then we can readily obtain, by the methods of dynamics, the increase in the mechanical displacement between the forced and the natural frequencies produced by resonance, or the " magnifying factor ", as it has been called by Messrs. Goerges and Rosenberg who have done such excellent work in the theory of parallel operation. This magnifying factor is infinite when the natural frequency equals the forced frequency, provided there is no damping. Under this condition, even with damping, however powerful, it is not possible in practice to obtain satisfactory parallel operation.

Turning now our attention to the Gary units, it was evident that if any measure of success was to accompany the construction of this plant, great forethought had to be exercised lest the successful parallel operation should be dependent upon a lucky guess on the part of the gas-engine builders. Therefore, before calculating the moment of inertia of the units, or the flywheel effect, extensive experiments were carried on to determine the natural frequency of oscillation of generators of similar design. The generators were run in multiple when the circuit-breaker was opened and closed again immediately. The number of complete oscillations per second could be counted and the natural frequency was thus actually measured.

These investigations, carried on with a number of different machines, over the entire range of the saturation, made it possible to determine beforehand the natural frequencies at all excitations of the Gary generators, and, therefore, under all conditions of load and power-factor. The curve in Fig. 1, marked " natural frequency ", shows the average result. The straight lines show the two forced frequencies of the gas engines. The points of intersection, *C* and *D*, mark conditions of instability, the range between them marking the range of stability. The operating range of the generators on the saturation and regulation curves, lies between *A* and *B*; and, therefore, is well within the range of stability.

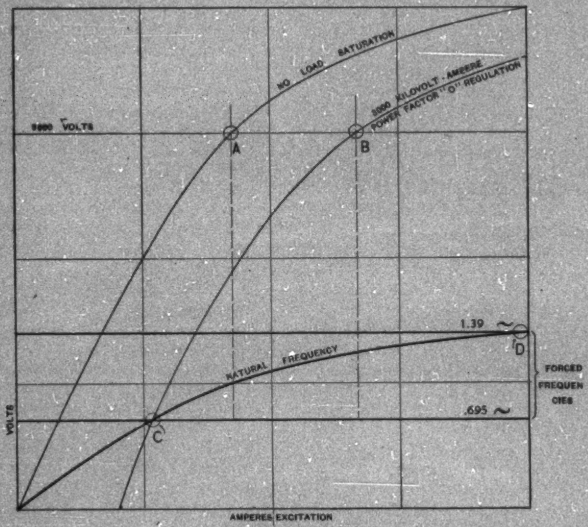


FIG. 1

Very light wheels had to be used to comply with the condition described. With light wheels, dampers are efficient and they have been provided on the Gary generators.

A flywheel effect of four times the flywheel effect used would have reduced the natural frequency below that of the lowest forced frequency, and the conditions would thus have been similar to those obtaining in steam engines. Such large flywheel effects on gas engines require the use of steel wheels of large diameter, which are not at all impracticable. In point of fact, the question was carefully considered whether large wheels, reducing the natural frequency, should not be installed. It was, however, finally decided to bear up with the greater fluctuations, and to install light wheels working between the two forced frequencies.

These brief remarks may suffice to indicate that the problem of multiple operation of gas engines has been reduced to an accurate scientific method based on careful experimental and practical data. While the details of the method, and the experimental data obtained, are beyond the scope of my present remarks, it should be mentioned that these methods have been applied to the plants of the Carnegie Steel Company at Rankin, Pa., where three 2000-kw. units are operating in multiple, to the plant of the Illinois Steel Company at South Chicago, where four 2000-kw. units are operating in multiple, and to the plant of the American Steel and Wire Company at Cleveland, Ohio, where four 1200-kw. generators are operating in multiple, and in all cases reasonably satisfactory parallel operation has been obtained. These plants are using blast-furnace gas and the generators are of my design. In another plant, generators of my design direct-connected to gas engines are operating on producer gas, using flywheel effects large enough to reduce the natural frequency below the lowest forced frequency.

Gano Dunn: My admiration for the work done at Gary is not second to that of anyone here. I feel without the slightest exaggeration that we are really considering one of the wonders of the world. I am reminded that the whole character of the Gary design is determined by the choice of prime movers, and that when we put our finger upon the quarter of a mile of gas engines we have placed it upon the heart of the plant. I also feel that, as Mr. Edison once expressed it, we are playing with blue chips, or as Mr. Carnegie once said, we have put all our eggs into one basket and are watching that basket. I believe so much attention has been put upon the gas-engine feature of the Gary plant that it simply cannot fail, and that the same intelligent engineering judgment which it is evident has been applied to other features of the plant, will be found to have been applied to the gas-engine equipment; and in the end, although possibly after some trouble, we shall have a wonderfully successful plant which will set a pace to be followed all over the country, and that gas will be used for the fundamental equipment of steel mills.

In the early days when direct-current motors were applied to steel mills, their duty was regarded as intermittent. Their continuous capacity then was low, but their intermittent capacity was extremely high. So great has been the progress in the evolution of steel mills, that this type of motor, originally designed for very intermittent service, has come to be the modern mill motor, subjected to a service that is more severe than continuous service, a service in which through rapid reversal and the encountering of enormous inertias, the duty on the motor is even greater than that corresponding to constant continuous load. Of course the adoption of very large units for roll driving meant alternating-current motors. Had direct-current motors been desirable for the great rolls they could not have been used, because the sizes are beyond the limits of direct-current design. The general judgment of everyone is, that the adoption of alternating current in the Gary plant for the major part of the distribution, has been a success. The battle may wage a little about the choice of current for auxiliaries and small distributions, and in this connection I am particularly interested in what Mr. Shover said of the desirability of an induction mill motor. He wanted an induction mill motor that would be as much better than the ordinary induction motor as the direct-current mill motor was better than the ordinary direct-current motor.

If he wants this earnestly enough I have no doubt he will get it. The same intelligent coöperation between the manufacturing companies and the consumer, shown at Gary in the production of the great induction motors for driving the rolls, undoubtedly will be shown again in the production of a good induction mill motor, but I question if in the long run Mr. Shover will want such a motor earnestly enough. An induction mill motor that is as much better than the ordinary induction motor as the direct-current mill motor is better than the ordinary direct-current motor, is still not as good as the direct-current motor. I am reminded of the remark made by Dr. Steinmetz on this platform not so very long ago, that if the frequency of a single-phase alternating-current motor were reduced, the characteristics of the motor were improved, and were best when the frequency was reduced to zero; that is, when direct current was used.

It is the advantages of generation and distribution that have brought the induction mill motor to the front, not good qualities in the motor itself. The low power-factors, the necessarily small air-gaps, the complexity attending the use of three phases with at least two sets of controlling apparatus, the great reduction in capacity for a given weight of motor; all in the end are bound to indicate that the problems of distribution ought not to be controlling to too great an extent, and ought not to cause the locating at every point around the mill where power is used, of the complications that attend an induction motor. They should rather lead to the collecting of such complications into a substation or power house where a motor-generator taking power from the main alternating distributing system will transform it into simple and powerful direct current to be sent out for local service.

It is my opinion that in the end our steel mills will not be supplied throughout with alternating current but will find themselves equipped with mixed systems of distribution—alternating current for the great powers and big motors, and direct current for the cranes, reversing motors, and other motors of similar service.

When the mill men first started electrical equipment, they were not in touch with the electrical men, and many mistakes were made. They were accustomed to steam engines and the measurement of power by indicators. On account of the difficulty of doing it, no one thought of measuring the power absorbed in accelerating. When motors were first used, acceleration was not yet a vital item, and many of the mistakes and failures of electric motors in steel mills have been due to the neglecting of the vast amount of power absorbed by the inertia of moving masses. The railroad men went through all this and developed speed-time curves. It was what Mr. Sprague, whom we heard last night at the annual dinner so correctly referred to as the "hero of Richmond", did not know when he put two 7.5 h.p. motors on a trolley car to do the work of two horses. Some of the most beautiful features of the Gary equipment are due to the appreciation on the part of the engineers of the characteristics of acceleration loads.

When I see how completely the steel industry has capitulated to the electrical engineer in the Gary plant I am filled with joy, remembering the attitude of the steel men toward electric motors not long ago, even on such innocent things as roll tables. Successfully to drive a roll table by motors was impossible. As for motors on the rolls themselves, you could not get a power station big enough to supply the current even if you could make the proper motor, which was doubtful. From such an attitude there has been victory after victory, until to-day we see one of the wonders of the earth completely electrically equipped. If the steel industry has capitulated to the electrical engineer, it is also true that the electrical industry has been developed by the requirements of the steel men, and has received the biggest kind of dividends from this development. It used to be said that electric railroad duty was the severest known to electric motors. It does not begin to approach in severity steel mill duty, and the modern mill motor, together with the great induction motors driving the rolls at Gary, indicates how the electrical engineer has responded to the steel mill demands.

It is a great night, gentlemen. It means much for the future, and we shall look back to this time, signalized by Mr. Shover's paper, as commemorating the solution of one of the greatest problems that electrical engineers have solved.

William T. Dean: Mr. Shover spoke very briefly on some of the problems which have been met; that is, whether the mill shall be two high or three high. A three-high mill is one having three rolls, each of which rotates constantly in one direction, that is, the upper and lower roll rotate in the same direction; while the middle roll rotates in the opposite direction, as indicated in Fig. 1.

A piece of steel, for instance, passes through the lower set of rolls at *A* to the right, the table is then raised and it passes through the upper set at *B* to the left. On the two-high mill where the steel must pass back and forth through the rolls, as indicated in Fig. 2, it is obviously necessary to reverse the direction of the rolls, and therein comes the difficult problem in electrical drive, especially when large motors are used. The mill must reverse quickly to prevent delay, and in this, very serious problems are encountered.

Mr. Dunn mentioned the use of direct-current motors on the rolls which, in some instances, may be as large as 6000 h.p. Such a motor would be extremely difficult to design, but if it could be designed it would be a very expensive machine. A plan worked out in Europe, where direct-current motors of large size are used on reversing rolls, is to put three armatures on a common shaft, thus reducing the inertia, on account of the diameters being smaller than if only one armature of large diameter were used.

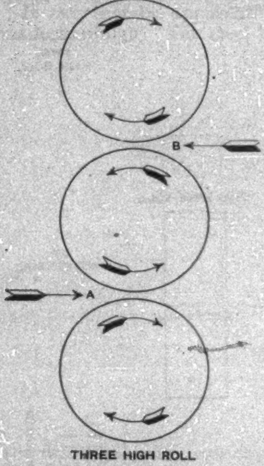


Fig. 1

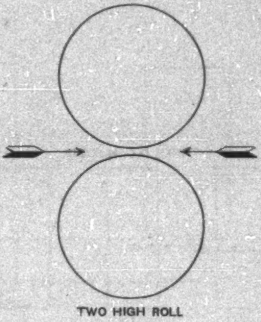


Fig. 2

Fig. 3 represents three direct-current motors, the armatures of which are mounted on a common shaft. As the mill reverses, it is impossible to take advantage of the mechanical value of flywheels; the enormous peak loads on reversal, therefore, are reflected back in the direct-current system, and to overcome this difficulty the three direct-current motors are electrically connected with two or three generators which are driven by an induction motor with a heavy flywheel, the generator armatures, motor armature and flywheel being on a common shaft, as shown in Fig. 4.

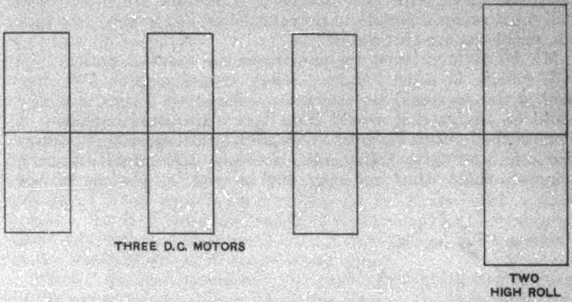

THREE D.C. MOTORS
TWO
HIGH ROLL

Fig. 3

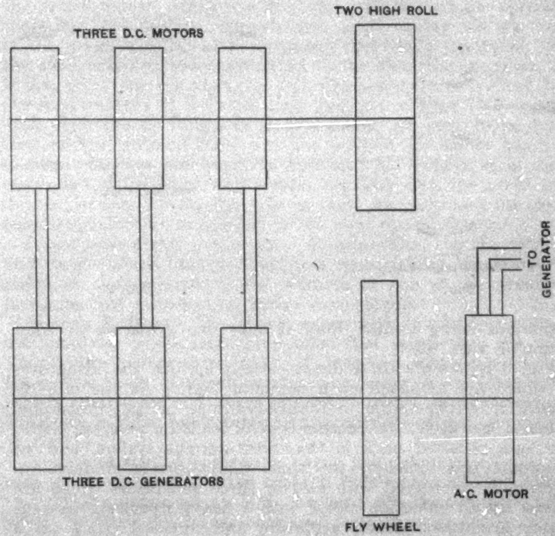

TWO HIGH ROLL
THREE D.C. MOTORS
TO
GENERATOR
THREE D.C. GENERATORS
A.C. MOTOR
FLY WHEEL

Fig. 4

If now it were possible to use a three-high mill instead of the two-high mill, the system becomes considerably simplified, inasmuch as the direct-current motors and generators can be omitted, and the induction motor can be directly connected to the rolls, as indicated in Fig. 5. The induction motor with its flywheel will do the work on any equipment, and the difference in first cost is just about one to three.

This is one of the problems which I think has been solved, in connection with the study of the Gary plant, it being first proposed to install a two-high mill, but after careful study it was found that the three-high mill could be used at about one-third the cost of the two-high equipment and with a large elimination of troublesome features.

It may not be apparent why a mill should have ever been made two-high. The steel business has been a gradual growth, the first steel being run through rolls driven by steam engines. The very first plan was to use small engines which were reversed at each pass, this practice having gradually grown to the larger work. Some of the older steel men do not believe, for instance, that universal plates can be made in any other than a two-high reversing mill, but some plants have demonstrated that they can be made in three-high mills, and by so doing, have greatly reduced the problems of electrical drive.

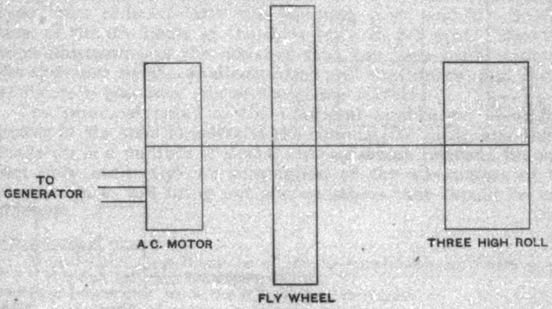


FIG. 5

On the subject of small alternating-current motors versus direct-current motors for driving auxiliary machinery in steel plants, I will refer to Fig. 6 which represents a small direct-current motor driving a roll table. In a system such as is used at Gary, this direct-current motor receives its power through a motor-generator set, the generator being driven by an alternating-current motor, which in turn receives its power from the alternating-current generators in the power station. If now an alternating-current motor were used on the roll table instead of the direct-current motor, the motor-generator set could be omitted by connecting the alternating-current motor direct to the power station through transformers, if such are necessary. After all, simplicity of general construction, as well as a general cheapening in the cost of the construction, is a highly important feature.

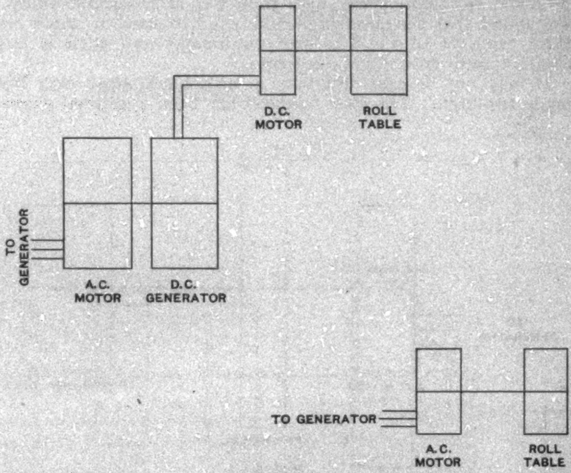


Fig. 6

Brent Wiley: Regarding the question of surplus gas power over and above that required by the furnace auxiliaries, a review of data obtained from several of the principal blast-furnace-plants abroad shows that the capacity installed per 100 tons of pig iron produced in 24 hours does not exceed 1500 h.p. The average pressure is approximately 8 lb. and the amount of coke burned per ton of iron produced is approximately 2400 lb. The author gives a surplus of 3000 h.p. per 100 tons of pig iron produced per day. I would like to have his opinion of a practical figure to use in this relation for comparatively small plants of more than two, and less than six, furnaces of modern type and capacity. My idea would be an average of the two values given above, that is, 2000 h.p.

Referring to the subjects of ore unloader and ore bridge, I wish to submit data on power requirements of machines which are similar to those described, and which are located at the Lorain works of the National Tube Company. Two of the unloaders have a total of 475 h.p., two machines a total of 525 h.p. and a capacity of 10 tons; the bridge has a total of 560 h.p., its capacity being 12 tons.

1 Unloader, maximum current 1200 amperes. Average current 500 amperes.
2 Unloaders and 1 ore bridge, maximum current 3300 amperes. Average current 1520 amperes.
4 Unloaders and 1 ore bridge, maximum current 6000 amperes. Average current 3500 amperes.
The voltage is 220.

With the older methods of unloading ore, where hand labor is employed to fill the conveying buckets, the unloading price per ton ranges from 12 to 18 cents, and for the boats of modern design ranging from 8000 to 1200 tons burden it would require several days' docking. Machines of the above-mentioned type have reduced both the handling price and the holding time of the ore boats at the dock fully 75 per cent. This is a good illustration of the advance that has been made with the development of the auxiliary steel mill machinery; and motor application has been one of the prime features.

The principal point of the universal application of electric power in the steel industry is the commercial value, and this is made up of a number of items, some of which relate to the subject only indirectly. A summation of the advantages of the electric drive will bring out the questions that should be considered.

Advantages of electric drive.

1. More reliable, less breakage of couplings, pinions, etc., with a correspondingly less maintenance cost.
2. Low power cost, with the following advantages:
   Centralizing of power equipment, low fuel cost, use of gas engines of medium size in power stations, uniform load conditions in power station engines by equalizing methods.
3. Less space on account of absence of boilers, pipes, etc.
4. Easy adaptation to mill machinery.
5. Easy distribution by means of cables, instead of steam or gas pipes.
6. Easy and simple handling with reliable protective features of control.
7. Less labor.
8. Less oil and other stores.
9. Ease of obtaining power indications and records.
10. Constant and regular torque.
11. Increased output due to higher and more uniform speeds.

As to item No. 9, economical conditions can be worked out and modifications made with a knowledge of results based on exact information, having available power indications and records which do not exist with the use of steam engines. Again, power indications are of valuable assistance in locating faults of machinery, a timely discovery of which prevents loss of time and material, and probably damage to the mill. The disadvantages mentioned by some engineers are high capital outlay, and loss of efficiency due to two intermediate machines between source of power and point of application.

Taking all the above items into consideration, however, the results are decidedly favorable to the electric drive, especially for new plants; and it will be found that there are comparatively few cases of existing plants, where the conversion from steam to electric drive is not worthy of the fullest investigation. This point is emphasized by the very active interest taken in the exhaust-steam-turbine proposition by a majority of the large steel companies. The exhaust steam from the existing mill steam engines is used to drive a low-pressure turbine connected to a generator which in turn furnishes electric power for the mill motors. Within the past two years the steel companies of the United States have installed more than 200,000 h.p. of gas engines and turbine electric station equipments, to drive approximately fifteen motor units aggregating 20,000 h.p., exclusive of thirteen units of the Indiana Steel Company now operating and on order and aggregating 51,700 h.p.

Within a year or so the data obtained from the above installations should give a conclusive analysis of the electric drive from both an actual and comparative cost standpoint, and while it is scarcely probable that this information will be available in detailed form, the electric companies are certainly justified in requesting that a review of the summary of the compiled data be made. It is to be hoped that attention will be given to the various phases of the question, bearing on such items as are mentioned under the heading "Advantages of the electric drive," in order that the full significance of the subject may be recognized.

The universal application of electric power at the Indiana steel plant, makes this subject of electricity versus steam a particularly fascinating one. In no other case has work of such magnitude or of such completeness been considered. Each mill proposition has been analyzed with great care and skill by the steel companies' engineers and they have outlined their conditions and requirements in a very definite and conclusive manner. The electric companies have appreciated this excellent work and as a valuable adjunct to his paper I would suggest that Mr. Shover add a copy of the specification, load diagram and data sheet items as furnished to the various electric companies for the rail mill proposition. This may appear to be an unusual suggestion, but a clear conception of this method of presenting a rolling mill proposition would further the development of the art to a greater degree of perfection, and this particular point is one of mutual interest and benefit to the steel and electric interests.

Robert Hull: The gas engine will have more and more to do in the manufacture of steel. An important question in the case of gas engines operating alternators is that of hunting, and I would like to have Mr. Shover give us his experience on any trouble with hunting he has had, and also some information as to the power-factor.

David B. Rushmore: It is my pleasure to-night to call attention to the fact that this is the beginning of a new era in the work of the Institute, and one which will be very closely associated with the administration of President Ferguson. It is interesting to note that for an illustration of the industrial application of the electric motor, it was necessary to go quite near to his own home. We have for years been familiar with the application of electricity in the telegraph, in the telephone, in lighting, in electric railway service, etc., but it has been only in machines of small size, and only in installations of comparatively small total capacity, that we have heard of the industrial use of the electric motor.

But we have in this installation the beginning of a new era in electrical work, where the application of electricity to industrial power more than takes an equal footing with the earlier application in other fields. In mill work, especially in this plant, we have very unusual conditions.

Owing to the limited time, it is desirable to confine my remarks to one phase of the subject. In this plant, with its many varied applications of electricity, two features stand out distinctly considering the scale on which they are practised in the manufacture of steel in this country. I refer, first, to the gas-engine power station. While such stations have been installed in other places on a smaller scale, it is the first time in this country that the complete power plant of a steel mill has been electrically operated. Secondly, I wish to refer to the drive of the rolling mill by electric motors. Smaller installations have been put in before, but nothing of this size, and nothing in the world has ever been attempted with machines of this capacity.

In rolling mills we have a number of varied problems, and it is very pertinent to repeat the remarks of the previous speaker to the extent that under no other conditions of service are the requirements of the electric motor as severe as they are in this work. The load curves we saw this evening on the auxiliary as well as on the main roll drive, indicate a load condition not met with elsewhere. This necessitates in the motor a very unusually strong mechanical construction and an interesting mechanical device mentioned by the author; it necessitates a comparatively large air-gap in the large machines, and also in smaller machines, making the design of the machinery, electrically and otherwise, with the idea of reliability first.

The author has very interestingly brought out the point that what a steel mill desires is nothing but the maximum output of steel, and the incidental features of the plant must all be designed with this in view. That means that the electric motors have a considerably larger air-gap than was necessary from any other consideration; that the factor of safety, electrical and mechanical, very much exceeds the figures that would be used for any other class of service, and as the author saw, in regard to the overload capacity of these motors, that no variation in temperature of ingots should be able at any time to stall them. This is illustrated in the new type, where all the mills operate continuously in the same operation, and all the motors are equipped with flywheels.

The design of a flywheel and the motor, with the automatic control, in order to have the motor properly function with its variation in speed, to draw the proper amount of energy from the flywheel and throw back on the power station the desired load, has been one of the very interesting problems of this work. Other engineers connected with the Steel Corporation have been studying, and have worked out with a very considerable degree of refinement the load thrown on the rolling mill by the reduction of the steel passing through it. This has been done to a large extent by the indicating steam engine, and now with the beautiful accuracy possible with the electric motor, a much more refined study of this problem will be possible.

The question of the alternating-current motors is a very vital one, and I wish to speak of it in connection with another engineer who has done a large amount of pioneer work for the Illinois Steel Company. This engineer is going to be the pioneer in introducing through the system which he is operating, high-speed rotary condensers, which entirely take care of the power-factor and the effect of the peak on the generating station. In this plant and in the other plants in which they will be used, these rotary condensers will give all the advantages of the electric motor, with the power-factor obtainable with zero frequency, as we have just heard.

President Ferguson: Before I call on Mr. Shover to close the discussion, I want to say a word which I thought of mentioning before, but as the hour was so late I omitted it. This subject of industrial power, not only as applied to steel mills, but to all practice, is really very important. It is not quite so pyrotechnic as some of the other things we have discussed, like the electrification of railways, for instance, but there is a great deal of work which is being done very quietly in the application of electricity for power purposes, but not nearly as much as should be done. It was with the idea of bringing out the possibilities of the use of electricity for power purposes generally that this year I appointed a commitee on industrial power, of which Mr. Rushmore is the chairman. It was hoped at this meeting that we would be able to have a discussion of more than one feature of the subject, but when we looked into the matter we found the application of electricity to power purposes in steel mills was so important, and involved such large quantities with such a great variety of applications, that we felt it was worthy of a whole evening, and I think we all feel that opinion is justified by the results of listening to Mr. Shover's interesting paper and the discussion which has followed.

We have arranged that the annual convention, if possible, should devote a session to the general subject of industrial power. We will then have a symposium on the subject, and discuss industrial power in all its phases, and we hope you will all be very much interested. I desire to let you know that this is only the beginning of what we think is a new and important work.

B. R. Shover: Mr. Hull's references to hunting and power-factor are important enough to require some comment. We have had some slight difficulty in paralleling the gas engines, but only at times of light load. The operation of the alternators in parallel under three-quarter load or more, is in the main as steady as that of any reciprocating steam-engine-driven alternators. On lighter loads there is always a tendency to hunt, due to inherent characteristics of the gas engine; for one cylinder is always a little stronger than the others, and one cylinder is a little weaker than the others. Therefore at light load there may be a point where the weak cylinder misses fire; this will be indicated by the needle on the ammeter, and the strokes of the engine can be counted at that time. If the weak cylinder and the strong cylinder act exactly opposite to each other there will be more or less trouble with the engine. I have never seen the engines thrown out of step, even under the very worst conditions, but sometimes I have thought that they would be. I do not think it is necessary to take up here the reason why it seems almost impossible to overcome this inherent characteristic of the gas engine.

The matter of power-factor was held up to us as a bugbear for a long time, so long in fact that we ceased to bother about it. We did not know what our power-factor was going to be; we had no way of finding out nor did we care what it was: there was nothing for us to do but to put in the plant, operate it, determine the power-factor, and then ascertain if changes were necessary. We have not yet reached the point where we can say what we are going to do, because the heavier the load on our plant the better the power conditions. When we get the mill full of steel we will know what the power-factor is going to be: at present it varies, according to the conditions in the mill, from 35 to 85 per cent.

A paper read at a joint meeting of the American Society of Civil Engineers, American Society of Mechanical Engineers, American Institute of Mining Engineers, American Institute of Electrical Engineers, New York, March 24, 1909.

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ELECTRICITY AND THE CONSERVATION OF ENERGY

BY LEWIS B. STILLWELL

In any problem, accurate and, so far as practicable, concise statement is essential to proper consideration and correct solution. The economic problems which present themselves when the complex and far-reaching subject, Conservation of Natural Resources, is considered, can be approached best by first stating and defining them with reference solely to physical and economic facts and relations without reference to political boundaries or limitations. To approach the subject by first considering real or supposed difficulties imposed by the respective rights and duties of states and of the nation, is to discuss method of treatment before diagnosis. We should first consider the problem as if there were no such thing as states within the Union, assuming, for the time being, the existence of one central and absolute authority within the federal boundaries. The question what is economically desirable upon this assumption, is that which the engineering profession should first agree upon and, if possible, state in a manner which will be understood by the general public.

Conservation as applied to our natural energy resources means utilization without unnecessary waste. In a broader sense it means also development along lines which will not only utilize but increase those resources; for example, as regards water-powers it has relation to the maintenance and renewal of forests affecting variation in stream-flow, and the construction of storage reservoirs which, properly used, are capable of adding greatly to that part of the run-off which can be used for industrial purposes and navigation.

Much has been uttered recently with reference to these relations which can not be expected to hold good in the light of that clearer knowledge which will result from further study and experience—much that is erroneous and misleading even when examined critically in the light of facts now ascertained and determined. General statements from sources commanding the attention and arousing the interest of the public are necessary first steps in turning a nation from reckless waste and almost unrestricted appropriation of natural resources by individuals, to a policy of wise conservation, having due regard to the common interest now and in the future. Those first steps have been taken, on the whole, in an admirable manner. Public attention has been arrested. Public interest has been aroused. Public and legislative opinions are forming. Obviously, it is of the utmost importance that our engineering societies should take an immediate and active part in working out the complex problems of conservation and, if possible, in directing the formation of public opinion along lines that will result in the enactment of just and wise laws.

The economic utilization of our natural resources is the fundamental problem of all engineering. If the President of the United States were to summon a conference of governors at the White House for the purpose of considering and promoting reforms in current medical practice, the medical profession undoubtedly would be greatly interested, and would manifest its interest by assuming proper and unchallenged prominence in discussing the questions raised. If such a conference were to assemble for the avowed purpose of initiating reforms in the machinery and methods for the administration of justice, it is not to be doubted that the lawyers would manifest their vital interest not only by exposition and discussion, but also by actual leadership.

The conference of governors in May, 1908, called by President Roosevelt to consider and advise regarding conservation of the natural resources of the United States, raised questions in respect of which the engineer occupies a position closely analogous to that which the medical doctor holds in respect of medical practice and the lawyer in respect of legal procedure and administration.

The analogy is not perfect, nor does responsibility for final decision rest exclusively upon the engineer, but it is peculiarly the patriotic duty of the engineering profession to enlighten the public by unbiased consideration and accurate exposition of essential pertinent facts, physical and economic.

I propose in this paper: 1. To illustrate the function of electricity in the conservation of natural resources. 2. To summarize statistically the present power requirements of the United States and present certain data (necessarily far from complete) relative to water power available. 3. To point out certain economic bearings of the plan which proposes the imposition of a tax on water powers, and the use of the proceeds for improvement and construction of inland waterways.

THE FUNCTION OF ELECTRICITY IN CONSERVATION

The part which electricity is destined to play in the conservation of our energy resources is demonstrated clearly by what it already has accomplished. Three typical illustrations will suffice: 1. The saving of coal by the utilization of water power, as illustrated by the plants of the Niagara Falls Power Company. 2. The saving of coal by the substitution of large and highly efficient steam plants for smaller and less efficient plants, as in the case of the Newcastle-upon-Tyne Electric Supply Company. 3. The saving of coal used for transportation purposes by the substitution of large and highly efficient engine units for comparatively small and inefficient locomotive units, as accomplished, for example, by the Interborough Rapid Transit Company of New York.

In each case the economy is due primarily to the fact that we can now use for transmitting and distributing power, the electricity produced in dynamos, distributed by conductors, and utilized by motors—all of remarkably high efficiency.

The Niagara Falls Power Company. During the year 1908, the plants of the Niagara Falls Power Company delivered an output of 560,000,000 kw-hr. Had this output been generated by large modern central stations using steam power, their consumption of coal would have approximated 2000 tons per day. Were the users of Niagara power dependent to-day upon their own individual steam plants, they would use in the aggregate not less than 3000 tons of coal per day; in other words, more than 1,000,000 tons per annum. If this power were replacing steam, as used under average conditions in our manufacturing cities, instead of being used for the most part in supplying power to a comparatively small number of customers using large blocks of power, it would replace and save nearly 2,000,000 tons of coal per annum.

Important as is the saving of coal from the standpoint of conservation of our natural resources, perhaps the most striking feature of the Niagara power enterprise is the demonstration which it affords of the great industrial value of cheap power, the greater part of the output of the plants being utilized to-day by electrochemical industries of great value to the community, all of which have been stimulated and some of which owe their very existence to their ability to secure power at very low cost.

The North-East Coast Power System. The North-East Coast Power System, supplying electric power to the great industrial district in and about Newcastle-upon-Tyne, effects a very important economy in coal consumption. In a paper presented at the Middlesbrough meeting of the British Iron and Steel Institute in 1908, Charles H. Merz, the engineer under whose able direction this large enterprise has been carried out, shows that the economies resulting from centralization of power development and electric distribution have led to the construction of plants now in operation, aggregating 102,000 h.p. installed; that additional plant aggregating 34,600 h.p. is under construction; that during the last 4 years the demand has increased at a rate averaging 20,000 h.p. per annum; that to-day every shipyard on the north bank of the Tyne is purchasing practically all of its power supply in the form of electricity; that the system is now

> responsible for the supply of current to eighty (80) miles of electrified railway, four tramway systems, the lighting in towns having populations aggregating over 700,000, motive power to the extent of 85,000 horse power and electrochemical works of over 12,000 horse power.

Not only has Mr. Merz established highly successful steam-driven power plants in a district where the cost of coal ranges from 7s. to 9s. per ton, but he has demonstrated that important economy of coal consumption results from the supply of electric power to the collieries for their mining operations.

Referring to this very interesting feature of the development, Mr. Merz says:

> The output of coal from Northumberland and Durham in 1906 was over 52,000,000 tons and, according to the Report of the Royal Commission on Coal Supplies, between six and eight per cent of the total coal brought to bank is used by the collieries for the purpose of power generation. From the make of coke * * * it appears that about one-fifth of the coal mined on the northeast coast is converted into coke. Making a liberal allowance, therefore, for the power at present used from the surplus heat resulting from the coking process, the collieries of Northum-

berland and Durham must burn for their power requirements some 2,500,000 tons of coal per annum. As the almost invariable rule is to work non-condensing, as the steam piping is usually long, and as a large portion of the load is intermittent, it is certain, and is proved by experience in this district, that the same power can be provided electrically in a large central power station by the consumption of less than a quarter of this coal. Apart, therefore, from the efficient utilization of waste heat, apart from the saving of coal in ship-building and engineering works, and apart from the saving resulting from the electrification of railways, the application of electricity to coal-mines in this district, when as complete as that to the Tyne shipyards, will render available for outside sale over 1¾ millions of tons of coal, equivalent to, say, over half a million sterling per annum.

The power plants of the Interborough Rapid Transit Company of New York. The output of the power houses of the Interborough Rapid Transit Company, New York, for the year 1908, was 409,000,000 kw-hr. The consumption of coal was 494,000 tons. In a paper presented at the 214th meeting of the American Institute of Electrical Engineers, by the writer and H. St. Clair Putnam,* comparison was made from the company's operating records of the fuel consumption upon the Manhattan elevated lines during the year ending June 30, 1901, when steam locomotives were employed, and during the year ending June 30, 1904, when electricity was used. I quote from this paper:

> Referring to the period first mentioned, one pound of coal produced 2.23 ton-miles, if the weight of the locomotive be included, and 1.5 ton-miles, if the weight of the cars only be considered.
>
> During the latter period (electric traction), one pound of coal burned at the power house produced 3.85 ton-miles; excluding weight of locomotives, therefore, the ratio of ton-mileage per pound of coal in favor of electric operation was 2.57 to 1. Including weight of locomotive it was 1.72 to 1.
>
> The average speed under electric operation was approximately 2 miles an hour greater than that attained by steam, and if correction be made for this difference, the ratio of ton-mileage per pound of coal, excluding weight of locomotives, is approximately 3 to 1, and, including locomotives, 2 to 1 in favor of electric traction.

If, therefore, we can conceive the possibility of operating today, by locomotives, the entire service of the elevated and subway lines of the Interborough Company, it appears that the saving in coal consumption effected amounts to not less than 988,000 tons of coal per annum.

In each of the three typical cases cited, it will be noted that electricity results in a radical economy of coal. That it also results in a material saving of household and other property which, in industrial communities using large numbers of small steam plants, suffer rapid deterioration by the effects of smoke and dust; that it tends strongly to improve the appearance of our cities and conditions which affect comfort and health, are facts not all of which are strictly pertinent to a consideration of the subject before us, but may nevertheless be mentioned in this connection.

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* TRANSACTIONS A. I. E. E., 1907. Vol. xxvi, p. 31.

Where steam is used to generate power in large plants from which electricity conveys it to users, economy results not only from the employment of comparatively large power generating units, but also from the introduction of plant economies and a degree of skill not attainable in smaller plants.

INDUSTRIAL USE OF POWER.

From the latest available census returns, the following tabulation of aggregate capacity of prime movers used in the United States at the dates and in the respective industries mentioned, is compiled:

	Installed horse power
Manufactures, census 1905	12,765,594
Mines and quarries, census 1902	2,753,555
Street railways, census 1902	1,359,289
Electric light and power stations, census 1902	1,845,048
Custom flour, grist- and saw-mills, census 1900, (omitted from census 1905)	883,685
Telephones, telegraph and fire-alarm systems, census 1902	3,148

The United States census reports since 1870 afford data from which interesting conclusions in regard to the respective rates of increase of power used for various industrial purposes, the relative proportions of steam and water power now in service and the enormous growth of electric motor applications may be investigated. Such a study has been made by H. St. Clair Putnam, of New York, and the results set forth in an interesting paper on "Conservation of Power Resources,"* presented by him at the conference on the Conservation of Natural Resources, held at the White House, May 13–15, 1908. Mr. Putnam employed the method of constructing curves based upon census statistics beginning with the year 1870, and projecting the resulting respective curves from the dates of the latest census figures to the year 1910. Making due allowance for the check to our industrial progress, which began in 1907, it is safe to say that at the present time the aggregate horse power of prime movers installed for industrial use in the United States, exclusive of steam railways, approximates 25,000,000.

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* PROCEEDINGS A. I. E. E. Vol. xxvii, p. 1397.

In round numbers, 50,000 steam locomotives are owned by our railway systems. Based upon maximum drawbar pull, these locomotives would be capable of developing about 30,000,000 h.p., but the average power actually developed on a 24-hr. basis, when averaged over the entire year, approximates only about 2,000,000 h.p.

Were all the railways of the United States operated by electricity generated in large and properly located power plants, the aggregate installed capacity of these plants would approximate 4,000,000 h.p.

Of the grand total of 25,000,000 h.p. installed for industrial purposes, exclusive of steam railway operation, water motors represent, in round numbers, 5,000,000 h.p., and gas engines and oil engines about 800,000 h.p.

I quote from Mr. Putnam's paper:

> Prior to 1870, the use of water power in manufactures exceeded that of steam power. Water power expressed in percentage of the total power employed has since steadily declined, falling from 48.3% in 1870 to 11.2% in 1905. During the corresponding period, steam power increased from 51.8% in 1870, to 78.2% in 1900. The census of 1900 showed a marked falling off in the rate of increase in the percentage of steam power used as compared with the rate prior to 1890, and this was accentuated in the census of 1905, when the percentage of steam power fell to 73.6% of the total. This check to the ascendency of directly applied steam power was due to the introduction of electric power. In 1890 electric power was negligible. In 1900 it constituted 4.8% of the total. In 1905 this had increased to 11.8%—a marvelously rapid growth when the aggregate increase of over 4,000,000 h.p. in five years is considered. If the present rate of increase prevails until 1910, electric power will have reached 18 per cent of the total and steam power will have dropped to 68%.

The facts to which I have called attention point unquestionably to further and rapid progress in the work of substituting electric motors for small steam engines. While this development has made a highly significant beginning in the field of transportation, in the replacement of steam locomotives for elevated and subway service and for terminal operation, it has already covered a substantial portion of the entire field of stationary operation. Its economies and their advantages are fast becoming matters of common knowledge. The cost of electric apparatus in general has decreased materially in the last decade, and the day appears not far distant when the isolated steam-engine plant as used for general industrial purposes will be practically banished from our cities.

Our ability to utilize in the near future a large proportion of our water-powers depends primarily upon the distance across which power can be electrically transmitted at practicable costs. This in turn depends upon the limits of potential against which transmission lines can be insulated in a manner which secures reasonable continuity of service. No precise limit of practicable distance can be fixed, nor is it necessary here to enter into a detailed discussion of the subject. It is sufficient to point out that power to-day is being transmitted from Niagara Falls to Syracuse, a distance of 160 miles. In California, it has been transmitted successfully a distance exceeding 200 miles. While 200-mile transmission does not bring every water-power of the country within reach of an adequate market, it does obviously suffice as regards a large proportion of our hydraulic resources not as yet utilized.

Available Water Power

From a purely physical standpoint, an estimate of horse power available in the case of a given stream requires accurate topographical survey and careful measurement of flow extending over a considerable period of years. Much work of very great value has been accomplished in these directions by the United States Geological Survey, but much still remains to be done. Systematic prosecution of this work is essential to the ultimate solution of our problems of power conservation, and the influence of the engineering profession should be strongly exerted to insure the effective extension and continuance of these surveys and measurements.

The majority of estimates of "water power available in the United States" which have been made, do not and cannot pretend to be exact. Obviously, there is a vast difference between the aggregate horse power which may be considered available, if the problem be looked at from a purely physical standpoint without reference to cost of development, and the amount which is available if cost of development and transmission to an adequate market is considered.

From the economic standpoint, determination of the aggregate, the horse power which a stream is capable of developing, involves a step-by-step examination of its profile from its source to its mouth, the approximate location of sites where the gradient and other topographical features indicate the practicability of development within the limit of practicable cost as fixed by cost of competing steam power, and the summation of the powers thus located. Following this general method, M. O. Leighton, chief hydrographer, United States Geological Survey, estimates the available water power of the upper Mississippi river and tributaries at 2,000,000 h.p. and that of the southern Appalachian region at approximately 3,000,000 h.p. The aggregate available water power in the state of Washington has been estimated at 3,000,000 h.p. and that of northern California at 5,000,000 h.p.; but these figures are merely approximations and cannot be regarded as authoritative.

The report of the Inland Waterways Commission acting as the Section of Waters of the "National Conservation Commission," before the recent Joint Conservation Conference in Washington, states:

> The theoretical power of the streams is over 230,000,000 horse power; the amount now in use is 5,250,000 horse power. The amount available at a cost comparable with that of steam installation is estimated at 37,000,000 horse power, and the amount available at reasonable cost at 75,000,000 to 150,000,000 horse power.

The assumptions and facts upon which these estimates are based are not set forth in the report referred to with that precision which is essential to correct judgment of their value. The amount named as "available at a cost comparable with that of steam installation," namely, 37,000,000 h.p., exceeds the aggregate mechanical power now in use within the borders of the United States, and suggests the enormous saving in coal which would result from anything like a general development and utilization of our water-powers.

But whatever may be the aggregate amount which ultimately can be utilized, certain guiding facts are obvious and cannot be controverted. Among these are: 1. Under average conditions every hydraulic horse power utilized for industrial purposes in 10-hr. service saves at least 7.5 net tons of coal per annum. 2. Present knowledge does not permit us to obtain from coal burned for power purposes, even under conditions of best commercial practice, more than 10 per cent of the energy which it contains; under average conditions less than 5 per cent is utilized.

3. Electricity enables us to substitute a few and comparatively efficient steam plants for large numbers of small and relatively wasteful installations, thus effecting important economies not only in fuel consumption but also in other directions. It also enables us to transmit and utilize in available markets a very large proportion of the aggregate water power of our streams.

In view of these facts, it will be admitted that from the standpoint of conservation of our power resources, the attitude of the federal and state governments should be such as will hasten and not retard the development of our water-powers. Any policy which operates to retard this utilization is a danger to the community, not only because it tends to increase the average cost of power and, therefore, of transportation and the manifold products of our manufacturing industries, but also because it tends to prolong and even increase the, at present, necessarily wasteful utilization of coal supplies which can never be replaced. Such a policy, therefore, is on its face in direct contravention of the true principles of conservation.

Water-powers not hitherto appropriated under existing laws belong to the state and unquestionably should be utilized in a manner which will secure the utmost practicable advantage to the community. There is every reason why they should not be appropriated in perpetuity either by individuals or corporations. In permitting their appropriation and use for a limited period, the state undoubtedly should obtain the best terms possible, but the fact that prompt utilization means not only a saving of coal resources but a reduction in cost of manufacture and transportation is a consideration of the utmost weight. As compared with the direct revenue which can be expected to result from levying a direct tax upon water-powers, this consideration, from a broad economic standpoint, is in all probability controlling. Doubtless the state *can* tax water-powers and *can* devote the proceeds of such tax to any special purpose which it may elect; for example, the construction of inland waterways, as has been proposed; but correct determination of the wisdom or folly of such an arrangement requires careful consideration and at least approximate knowledge of the quantitative values of the economic results to be expected.

In a short speech before the Conference of Governors at the White House in May, 1908, referring to water-powers, President Roosevelt said:

> My position has been simply that where a privilege, which may be of untold value in the future to the private individuals granted it, is asked from the Federal Government, that the Federal Government shall put on the grant a condition that it shall not be a grant in perpetuity. Make the term long enough so that the corporation shall have an ample material reward. The corporation deserves it. Give an ample reward to the captain of industry but not an indeterminate reward. Put in a provision that will enable our children at the end of a certain specified period to say what in their judgment should be done with that great natural value which is of use to the grantee only because the people as a whole allow him to use it. It is eminently right that he should be allowed to make ample profit from his development of it but make him pay something for the privilege, and make the grant for a fixed period, so that when the conditions change, as in all probability they will change, our children—the Nation of the future—shall have the right to determine the conditions under which that privilege shall then be enjoyed.

With the ideas thus vigorously expressed, every good American citizen must be in sympathy. To the admirable exposition of principles included in the preliminary report of the Inland Waterways Commission, dated February 26, 1908, few engineers will take exception. But the attitude of some of the speakers at the recent Conservation Conference in Washington, upon the occasion of the second gathering of the governors of the states, clearly evidenced a disposition to beg one of the fundamental questions which arises at the very threshold of consideration of the utilization of our streams; namely, the question of the real economic value of inland waterways. The minds of some who are taking an active part in the discussion of this great economic question apparently start with two assumptions: 1. That the economic value of a vast system of inland waterways is admittedly so great as to justify practically any expenditure in its development. 2. That the water-powers upon our streams are inexhaustible mines of wealth capable of yielding, under a general system of taxation, large revenues. From these premises, the conclusion that water-powers should be taxed to pay for waterways is easily deduced.

To the engineer it is evident at once that before any conclusion, involving expenditure of large amounts either of public money or private capital, is agreed to, both premises upon which that conclusion is based should be critically examined.

I do not propose in this paper to attempt anything purporting to be an exhaustive discussion of this complex subject. Personally I am frank to admit I have found it impossible from my present knowledge to form definite and final opinions in respect of some of its phases. If our national engineering societies, during the coming year, will secure from their members best qualified by special knowledge to supply pertinent facts and suggestions, carefully considered papers discussing the comparative economics of transportation by rail and by inland waterways, much light will be thrown upon this very important and far-reaching question. At present data apparently essential to well-grounded judgment have not been collected and compared in a manner to justify formation of definite and final opinions which can be expressed in precise terms, opinions which may be expected to stand the test of time.

In calling attention to certain considerations which apparently tend to controvert the present popular impression that a radical improvement and extension of our inland waterways is the natural and proper solution of the great problem of freight transportation, I trust it will be understood that I am not approaching the subject from the standpoint of one whose interests are identified with railways. Such is not the case. The electrical engineer has everything to gain and probably nothing to lose from a policy which during the next 10 years may result in the appropriation of from $50,000,000 to $100,000,000 per annum for the improvement of our waterways and development of our water-powers. An engineer's first duty in a case of this kind is to bring any special knowledge which he possesses to bear upon the economic problem presented, to form and to state his opinions absolutely without bias. In our offices and in the field we may be retained properly to represent this or that special interest, but on the floors of our engineering societies our proper attitude is that of the man of science interested solely in the facts, their causes, relations, and consequences.

In considering the proposition to impose a tax upon water-powers and to devote the proceeds of this tax to the construction of a system of inland waterways, it is clear that the first effect of such a tax would be to retard the development of water-powers unless some compensating advantage were offered. It is also evident that such a tax would operate indirectly to stimulate the consumption of coal, and that if it be decided that we can afford to tax manufacturers indirectly in order to improve transportation facilities it would be wiser, from the standpoint of conservation of our power resources, to impose a tax upon coal used for power purposes. A tax of $3.00 per horse power

($4.00 per kilowatt) per annum is equivalent to a tax of 40c. a ton (2000 lb.) on coal used for power purposes in manufacturing, if we assume that 5 lb. of coal per h.p.-hr. are used. A proposal to impose any such tax on coal used for power purposes and use the proceeds for the construction of inland waterways probably would command little influential support, and yet a similar proposal, as applied to water powers, has received weighty endorsement and apparently is highly approved by those who are especially interested in the development and extension of inland waterways.

In the report of "The Inland Waterways Commission, acting as the Section of Waters of the National Conservation Committee before the last Joint Conservation Conference," I find the following referring to the uses of water power in our streams:

> The paramount use should be that of water supply; next should follow navigation in humid regions and irrigation in arid regions. The development of power on the navigable and source streams should be kept subordinate to the primary and secondary uses of the waters; though other things equal, the development of power should be encouraged, not only to reduce the drain on other resources, but because properly designed reservoirs and power plants retard the run-off and so aid in the control of the streams for navigation and other uses.

It would be interesting to know how the conclusion has been reached that in humid regions the development of power on our streams is less important than the improvement of navigation. To one familiar, for example, with power developments in the cotton-mill district of the Carolinas, and with the character of the streams there utilized so extensively and with such vast advantage to the community for power purposes, the idea that any conceivable use of these streams for purposes of navigation can be comparable to their value as producers of power is, to say the least, highly improbable.

Obviously, before any such general policy as that recommended is adopted, we should have assurance that the imposition of such a tax will not cost the community more than the resulting improvement of transportation facilities is worth. Cheap power is a factor of great importance, both in manufacturing and transportation. According to the census of manufactures taken in 1905, the gross output of our factories and mills had a value of $16,866,706,985. This product represented $1,152.00 per horse power installed. The wages paid amounted to $248.00 per horse power installed.

In the same year, the aggregate gross receipts of our railways were $2,325,765,167, or about 14 per cent of the value of manufactured products.

The object sought in constructing inland waterways is reduction in cost of transportation. The proposal to impose a tax which will operate to increase costs, in a business amounting to nearly $17,000,000,000 per annum, in order to attain an undefined advantage in reduction of cost in a business of less than one-seventh that amount calls for something further in the way of analysis than has yet come under my observation in this connection. The fact that manufacturing costs in America are in general much higher than in Europe, while our cost of transportation per ton-mile is now materially lower than can be found elsewhere, emphasizes the impression which results from a moment's consideration of the respective gross volumes of business in these allied fields of industry.

It would be impossible to suggest a more fruitful subject for unprejudiced analysis and illuminating exposition by competent members of our national engineering societies, in the immediate future, than the comparative economic advantages of railways and inland waterways. Facts in this field are urgently needed and should be supplied before public sentiment, unenlightened by unbiased competent advice, and influenced, perhaps, by prejudice and the clamor of local interests, shall crystallize in legislative enactment or executive rulings. Within the last two years, my firm, in considering problems presented by the substitution of electricity for steam in railway operation, has carefully studied the cost of operation of steam railways in the United States, using as the basis of this investigation not only the valuable reports of the Interstate Commerce Commission but also detailed operating cost-sheets confidentially furnished for the purpose by a number of the most important railways in the country. It also happens that within the same period we have had occasion to determine with great care the actual cost of operation of one important canal system, and in this connection we have secured considerable information bearing upon the general question of the economics of canal transportation. The conclusions which we have reached as a result of these comparative investigations do not support broadly and without material qualifications the popular impression that transportation of freight by inland waterways, in general, is less expensive than transportation by railways.

In engineering matters, general statements almost invariably are subject to exceptions and I am not prepared to assert broadly that the construction of canals for transportation purposes is a mistake. I do assert, however, that in the majority of specific instances that have come under my observation the facts are far from justifying, from an economic standpoint, a propaganda aiming at the development of a general system of inland waterways beyond what may be attained by reasonable improvement of the channels of navigable streams with such comparatively short inter-connecting canals as may beyond reasonable doubt be justified by the results attained.

As regards the proposed " concurrent development of the streams and their sources for every useful purpose to which they may be put ", as it is stated in the " declaration of principles " of the recent North American Conservation Conference, all engineers will agree that each stream should be studied with reference to its possibilities " for domestic and municipal supply, irrigation, navigation and power as inter-related public uses." But the development of a plan economically sound calls for unbiased consideration and fairly accurate knowledge of the economic value to the community of the resulting improvement of the stream regarded as a waterway for transportation. Obviously if we begin by assuming that because freight is carried across the Atlantic or through the Great Lakes at less cost per ton mile than it is carried by our railways, an increase in the depth of channel or improved regularity of flow of any given inland stream will secure corresponding results, we shall be misled and expenditures based upon any such assumption will be wholly or largely wasted. Each case should be studied, and competently studied, on its own merits. To tax water powers for the purpose of providing free waterways, from a broad economic standpoint, is a policy which, before adoption, should be compared carefully with the plan of imposing tolls upon all users of inland waterways and using the proceeds to develop water powers and secure cheaper power for our manufacturing industries.

The declaration of principles agreed upon by the recent North American Conservation Conference makes the following statement:

> We recognize the waters as a primary resource, and we regard their use for domestic and municipal supply, irrigation, navigation, and power, as interrelated public uses, and properly subject to public control. We, therefore, favor the complete and concurrent development of the streams and their sources for every useful purpose to which they may be put.

In the preliminary report of the Inland Waterways Commission, dated February 26, 1908, I find the following:

> While navigation of the inland waterways declined with the increase in rail transportation during the later decades of the past century, it has become clear that the time is at hand for restoring and developing such inland navigation and water transportation as upon expert examination may *appear to confer a benefit commensurate with the cost*, to be utilized both independently and as a necessary adjunct to rail transportation. [The italics are mine.]

The fundamental facts here set forth will receive the unanimous and enthusiastic endorsement of the entire engineering profession. In determining, however, how the admirable and vastly important objects in view are to be attained, every engineer should use his best endeavors to prevent fundamental and far-reaching mistakes which easily may result from action based upon insufficient or inaccurate knowledge.

DISCUSSION ON "ELECTRICITY AND THE CONSERVATION OF ENERGY." NEW YORK, MARCH 24, 1909

John Coffee Hays (by letter): In arousing public interest in the conservation of our natural resources the impression has been generally given in discussions and newspapers and magazine articles, that there was a very much larger waste going on than actually exists. It would seem, therefore, that the time is now at hand for engineers to discuss the different points of the question more in detail, and to show what work has already been done in the direction of conservation, and what in their opinion should be done in the future toward the use of our resources in the most economical manner. From the very nature of the work, engineering is more closely connected with the conservation of resources than is any other profession, and the engineer should lend every effort in his power to the general education of the public in this respect, and should discuss the various points of the subject practically and forcibly in line with his convictions and experience.

In the papers presented before the joint meeting of the four national engineering societies on the evening of March 24, it was clearly shown that very great work had been done in the past generation in respect to the economical use of our natural resources. The paper presented by Mr. Lewis B. Stillwell clearly pointed out the large part that electricity was accomplishing in this direction, and it is in line with this paper that I wish to discuss briefly the position of the water-power developments in the far West.

The writer in the capacity of consulting engineer to several of the largest hydroelectric projects of California has had the opportunity to make a close study of the subject on all sides, and particularly as to the policy of the federal government in connection with power projects in the forest reserves and national parks of California, and the effect that the present policy of the Department of the Interior has on the development of these projects which comprise practically all of the present available undeveloped water-powers in the state.

The water-powers have probably attracted more public attention in the last two years than any of the other natural resources, as they are the only ones which will not be exhausted by use. This fact makes it natural for the layman to assume that "the great water-power monopoly" which the press and the magazines frequently refer to, is a grave calamity facing the public, especially when the high officials of our government express similar opinions. The writer, of course, agrees that if in the distant future a monopoly were formed comprising all of the water-power in California—provided such a monopoly could be formed over which the federal government and the local authorities had no control—that it would be detrimental to the public interests when the natural supply of fuel was exhausted. But even under the present laws of the state it does not seem possible that any extortion could be practised even were the water-power business controlled by one company; for the governing body of every community, be they supervisors or city trustees, has the power to regulate the rates of any water-power or any other public service corporation.

It is not my object to discuss whether or not a water-power monopoly threatens the people of California; what I wish to discuss is whether the present policy of the government is beneficial in checking a monopoly, or detrimental, by preventing the development of one inexhaustible natural resource and therefore necessitating a greater use of our exhaustible resources, such as oil and coal.

It should be clearly understood that the state and not the federal government owns the water in all of the streams available for power developments in California, and that the state has enacted laws which clearly set forth the manner in which this water is to be diverted and used. In the case of the forest reserves and the national parks, the government owns the land through which the streams flow, and therefore the only way that the government can control this development, is due to its ownership of the lands on which the conduits and power stations must be constructed. Where land along a stream is held by an individual, it may be condemned by a power company, the owner receiving compensation only to the amount of the actual damage done his property. As the land along these streams is useful only for grazing purposes, the damage is very slight, not greater than a few dollars per acre for a right-of-way 50 or 100 ft. wide, the entire length of the conduit; in fact, a private owner often grants this right-of-way to the power company free of charge. The riparian right, which entitles the land owner to the amount of water necessary for the irrigation of his lands, is his only other right; but in the mountain districts, owing to the character of the land, there are very few cases where the land is fit for agricultural purposes and therefore irrigation is not required.

The primary object of the forest reserves was to protect the timber thereon, and therefore should include only timber lands. This being the case, the majority of available power sites, which are at present embraced in the forest reserves, should not be affected, as the land on which these sites are located is in most cases below the timber line, and would consequently be outside of the reserves. However, the present forest reserves take in complete watersheds from the highest peaks several thousand feet above the timber line, to the edge of the valleys several thousand feet below the line of the marketable timber, as in these lower altitudes only the small trees and brush are native. It would appear therefore that the boundaries of the forest reserves were set with the idea of controlling the water-powers. The forest department makes a point that owing to the protection of the forest they maintain the streamflow and therefore should be entitled to regulate the use of the water in the streams so far as the streams lie within the reservation. It is generally accepted that the forests act as natural reservoirs in the regulation of streams; no doubt this is correct in respect to the eastern states where the mountains are comparatively low and heavily timbered, but in the far West we have a rather different condition as far as the water-power developments are concerned. I wish to venture the opinion that the forests on certain watersheds in parts of the Sierra Nevada mountains are of comparatively little advantage to the power company; for in these cases the timber line is far below the crest of the range. It is the melting snow on these barren rocky slopes above the timber line which gives the water during the lowest water period of the year, there being very little run-off from the forest portion during this time.

It is the aim of the federal government, the state, and all conservative men connected with water-power development to discourage the practice of irresponsible parties filing an appropriation notice on a stream, and then holding the right for speculative purposes. Under the state law, after posting a notice on a stream and filing a copy of the notice, the appropriator must within 60 days of the time of filing his notice begin work and continuously prosecute it to completion with due diligence. Where the stream lies within a forest reserve the state law has been amended to the effect that within 60 days after the filing of the notice, work must be started in the form of a survey for the preparation of an application to the Department of the Interior, and after receiving a permit from the Department of the Interior, work must be started within 60 days, as above, and pushed to completion within the time specified in the permit. The Department of the Interior allows one year for the making of the survey and the filing of the application, and as a considerable amount of time is necessary for investigating the project before an application is granted, it can mean from 18 months to two years before actual construction work is necessary. If it is a case of speculation, the speculator has really more time and is in a more comfortable position when his appropriation lies within the reserve than when it lies without. In the investigation by the Department of the Interior before granting a permit, it is the aim to ascertain the feasibility of the scheme as well as the financial responsibility of the appropriator, and were this investigation pursued thoroughly and with a view of developing a watershed of the highest efficiency, it would no doubt be of great advantage. At present the department is not in a position to do this, and the question of feasibility and financial responsibility is left largely to the judgment of the local forest ranger who is incompetent to judge of these matters, owing to the fact that the majority of these rangers have been born and reared in the mountain sections; while they are usually admirably fitted for their position as far as the guarding and protecting of the forests are concerned, they have neither the education nor experience which would enable them to pass intelligently on a power project or anything relating thereto.

While in the case of the state's requirements the diligent prosecution of the work until completion is often interpreted to mean a very small amount of work by the speculator, it does not seem that the government requirements have bettered the matter to any extent. It would seem that the state at least had the advantage of simplicity, for should the appropriator not prosecute work with diligence, and not be in a position to prove that he had lived up to the requirements, he is in constant danger of having some one else make an identical filing, and push the construction of a plant to completion, thereby leaving him without anything; for no rights of any kind are obtained under the state law until the water is actually diverted and used, when the right is then acquired and dates back to the time of filing the notice of appropriation. While it is held by most of the water-power companies and many authorities that the government has no right to control the water-powers within the reserves simply because it has acquired land, it is my opinion that were the regulations and requirements of the forest department at all reasonable, they would meet with very little opposition from the power companies. It is further my opinion that practically all the opposition is caused by the revokable form of permit, and the so-called conservation charge made for it.

As to financing property and affording any protection to the stockholders of the power company, a form of permit which is revokable at the discretion of the Secretary of the Interior is worthless, especially when some of the absurd conditions which are imposed in the present form of permit are taken into consideration. The permits as now granted, mean that if at any time a company has not, in the opinion of the Secretary of the Interior, lived up to the conditions imposed and the rules and regulations of the department, the permit may be forfeited, and a plant representing the investment of millions of dollars be confiscated by the government. One of the absurd clauses in the permit is to the effect that the company shall not break any of the game laws, which means that should an employee catch a fish, or shoot a deer out of season, the company would be liable, and its permit could consequently be revoked. It is of course impossible for a company to be responsible for its men to this extent, and it is further absurd when it is considered that the breaking of a game law is a state and not a federal government offense, whether it be within a forest reserve or without.

While the conservation charge or the tax on the permit, is comparatively small at present, it is also subject to change at the discretion of the Secretary of the Interior within specified but broad limits. Aside from this it is open to considerable question as to whether or not the government has any right legally—it is manifest that it has no right morally—to collect this tax; for by so doing it forces the power company to charge a higher rate for power, thereby placing it in the position of tax collector for the government to collect from the people of a comparatively small community, thereby throwing an additional tax on the citizens served. There has been considerable discussion as to what use this money could be put, and it is generally considered that it might be used for the improvement of inland waterways or applied toward the expenses of maintaining the forest reserves. Mr. Stillwell in his paper discussed the matter of taxing water-powers for the improvement of the inland waterways, and I will therefore pass over this point. However, as regards the application of this money toward the maintenance of the forest reserves, it would appear manifestly unjust from the simple fact that the forest reserves are created and controlled by the federal government and any expenses in the maintenance of them should be borne by all the people of the United States, and not by the people of a comparatively small community who derive little if any benefit from them. It is also impossible to state any fair rate of taxation which would be applicable to all water-powers, as each power is peculiar to itself, and the cost of construction varies within wide limits, whereas the market value for power is practically the same, so that a tax which would not be felt by one company might be ruinous to another.

This discussion is not intended in any way as an attack on the principle of government regulation of water-powers, and were this an entirely new industry in a new country having no laws governing the streams, or should the title to the waters of the streams pass to the government with the lands, it would be an entirely different proposition, and might be handled by the government to advantage. The fact is, however, that this is not a new industry, and that well-defined state laws have been enacted and in force for years. When it is taken further into consideration that the government lays absolutely no claim to the waters of the streams, it would seem impracticable and extremely unjust for the government in the form of a landowner to stifle the development of one of our most important industries, and the present policies of the Department of the Interior can have no other effect.

There is of course, a popular feeling and a natural one, that perpetual water rights should not be held by any individual or corporation for power purposes, still the state laws provide that this may be done, and it would seem that if a time and limit were to be put on a water-power, the only way to accomplish it would be by the changing of the state law and not by revokable permit. A water-power is of necessity a monopoly to a certain extent; that is, to the extent that a street railroad franchise is a monopoly on the street during the life of its franchise. The power company's monopoly is confined simply to its position on the river and its right to use a certain amount, or all, of the water for power purposes at this point, but these rights do not give it a monopoly of the market, for should it charge its consumers a high rate for power it would immediately court competition, and a power company on an entirely different river could extend transmission lines into the territory served, for it must be remembered that electric power is being commercially transmitted hundreds of miles with an extremely small loss of energy.

The present condition could be relieved to a great extent, however, by a very simple means; that is by the granting of an irrevokable permit by the Department of the Interior to the water-power company for a certain definite period, and making a definite provision for the disposal of the property at the expiration of this grant. All the absurd conditions of the present form of permit should be omitted, and if there must be a conservation charge, a definite sum should be set for the entire period. In this way the power company would know exactly the position it was in, and the conditions which it would be necessary to meet. As to the disposition of the property at the expiration of the permit, it should be decided whether or not the power company should simply give up all its property at this time, whether it would be taken in by the government at a predetermined cost, or whether it would be sold at public auction. If the power company were to release all rights at the end of the period, it would of course necessitate laying aside a sinking fund to pay for the installation, which would throw a burden on the consumer, in that it would necessarily increase the cost of the power production.

As to the government control, during the term of the grant, to prevent extortion by the company, I am of the opinion that very few people aside from the government officials and magazine writers consider this seriously, as the state has laws which amply protect citizens from any extortion by power companies, and the government should therefore let the power company entirely alone during the term of its grant. At the expiration of the grant, the property would come again under the control of the government for its disposal, when it might make any changes which in the meantime had proved would be of advantage. In making any regulations, the fact cannot be overlooked that some incentive must be held out to capital in order that this power be developed, and these absurd difficulties which have been placed in the way of power companies by the Department of the Interior must be removed, before a hydro-electric project is considered in any other way than a most undesirable investment, as is the case to-day.

While it is the general impression that a monopoly of any kind is not beneficial to a community, it has also been proved that a large producer may operate more economically than a small one. This point is particularly noticeable in the development of the water-power in the far West, owing to the great distance of markets and the advantage of combining the output of several hydroelectric power stations and distributing current along the same transmission lines and so placing the power stations that the available water may be used several times, and in a more economical manner. It does not follow that all the water-powers in the state should be combined, but the writer believes it is absolutely necessary for an economical development of any stream, that all power installations in the watershed be under one management, so that the entire watershed may be treated as a unit and worked to its best advantage. In a case that I have in mind, approximately 50 per cent more power could be developed from the watershed were it held by one company than could be developed by two rival companies.

This is the case where the storage reservoir capacity would be on the small tributaries of the main river. With a generating station situated on the main river, the water from these tributaries could be stored during the high water season, when there will be plenty of water in the main river to operate the plant, and during the low water season the flow of the main river could be reinforced with the stored water in the reservoir, thereby keeping the plant up to full capacity. Now assume that one company owns a generating station on the main river and a rival company holds the reservoir sites on a tributary, and that no reservoir sites are available on the main river; the plant being supplied on the main river would of necessity be installed for a capacity equal to the minimum flow of the river during the low water season, while the plant on the tributary would be installed for the average yearly flow of that stream, as both stations must be operated at full capacity for 365 days a year. When it is taken into consideration that the minimum flow of the rivers of central California is not over 5 to 10 per cent of the average yearly flow, it will be clearly seen that without storage reservoirs there would be an enormous amount of water going to waste during the high water season.

The condition above assumed is the rule rather than the exception, in that it is a difficult matter to find storage reservoir sites on the large streams, and when available they are usually very expensive to develop, whereas on the smaller tributaries there are often mountain meadows, lakes, etc., which may be more practically converted into reservoirs by the construction of comparatively cheap dams, where almost the entire run-off of the tributary may be stored during each year, to be used later in reinforcing the main stream. The construction of reservoirs for water-power purposes is also a great advantage to the country in the valleys, as it reduces the water in flood periods and conserves it for use for irrigation later in the season when it is greatly needed, and this point alone should serve to gain support for a water-power development. Unless each watershed is taken as a whole, and studied with a view to the most economical development, it is apparent that a great waste would ensue which would be almost permanent, as a properly installed plant represents a great deal of invested capital, and anyone would seriously hesitate before abandoning it, even for the purpose of effecting a more economical arrangement.

As to the position the existing water-power companies hold to-day, it would be gathered from the sensational utterances of the press and the skilfully written articles in some of the magazines (which however are not always based on facts) that even to-day a water-power is a monopoly, and that the people are suffering through them. It would be well, therefore, to look at a little of the work which has been accomplished by the development of some of our western water-powers, and the case I will cite, being a power company supplying power to a strictly agricultural community in the San Joaquin valley, is, I think, one of the best examples of the conservation of a natural resource that I have encountered. This company began operation about ten years ago, and its territory comprises a section of approximately one million and a quarter acres of land. At that time approximately 90,000 acres of the land was under irrigation, and all of the water in the natural streams was diverted and used, so that the remaining land which was most suitable for the raising of high-class products, when irrigated, was of necessity undeveloped owing to the lack of water, and was used only for the growing of grain and for grazing purposes. About this time it was discovered that approximately 150,000 acres of this land lying along the foot-hills was exceptionally well adapted for the raising of oranges and other citrus fruits, and as the profits on these products are extremely large, endeavors were made to irrigate these lands by pumping water from wells. Gasoline and steam engines were used for pumping, but owing to the unreliability and cost of operating these engines by unskilled men very little was done.

With the advent of electric power the country developed rapidly, and this rapid development continues. There are at present over 20,000 acres of land planted to these products, irrigated by water pumped from wells by electric motors, and the gas engine and steam engine have completely disappeared from the field. The value of the land which at the advent of electricity was from $2 to $10. per acre has increased to as high as $400 per acre, and the orange grower makes an average annual net profit of approximately $250 per acre. This $250 is interest on an investment of approximately $500 including the land at $100. per acre, the remainder being spent in planting and caring for his orchard for the first five years, when it comes into bearing. The irrigation which makes all this possible, costs on an average about $10 an acre per year for the power used, as the price charged is $50 per horse power per year, and one horse power used in this way will irrigate on an average five acres. It may be farther noted that the cost of harvesting, raising and shipping the crop amounts to from $300 to $500 an acre, when the net is $250, and it is therefore apparent that the power charge is an insignificant item of the expense, and that the consumer is not being very badly robbed by the power company, magazine articles to the contrary notwithstanding. The rate of $50 per horse power per year is often compared with such prices as are charged at Niagara where thousands of horse power are sold to one consumer, whereas in this case the average size motor used is 7½ horse power. In a plant such as Niagara the installation is comparatively cheap owing to the large units, the short conduits, and the accessibility of the plant, but in the western plant mentioned, the output is comparatively small, and the plant is located many miles from a railroad, requiring the transportation of all machinery and material over rough mountain roads at great expense. The conduits are long, and constructed along steep mountain sides, thereby making the expense of hauling and hoisting one of the largest items of construction. The investment in distributing lines alone, due to the marketing of the power in small quantities over a wide area, amounts to approximately half as much as the cost of the rest of the plant. This illustrates also the necessity of treating each water-power separately when considering profit on prices charged, as all the water-powers which the writer has investigated operate under entirely different conditions, and it requires a very thorough knowledge of any plant to be able to discuss it, or the rate of charges, with any degree of exactness. This knowledge of the property can be gained only by an examination in the field. The plant described operates on rivers, the waters of which are used exclusively for irrigation. One miner's inch of water will irrigate about 5 acres in this section. The water-power company uses the water in the mountains and turns it back into the stream, whence it flows out to the valley and is used for irrigation, while the power-house transforms the energy of this water without diminishing it, and also sends to the valley in the form of an electric current over wires, energy which is used for the pumping of additional water from the underground reservoirs, and therefore is another irrigation project. In the above mentioned system approximately 100 second-feet are used and with this is generated approximately 7,000 h.p. which may be delivered to the pumping plants. Of this 100 second-feet a large proportion is of course lost in evaporation, seepage, etc., before it is applied to the land, but assuming that it were all delivered and placed on the land for irrigation it would be capable of irrigating about 20,000 acres, but in passing through the power-house it also generates enough current to irrigate approximately 35,000 acres by water pumped from wells. It can be seen that this is indeed conservation in its highest form.

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HIGH-VOLTAGE TRANSFORMERS AND PROTECTIVE AND CONTROLLING APPARATUS FOR OUTDOOR INSTALLATION

BY K. C. RANDALL

Outdoor or weatherproof transformers for ordinary distributing purposes, and for potentials up to about 2500 volts, have long been in general service. With the exception of arc lamps and series incandescent lamps, transformers have been about the only apparatus in high-tension service not protected by buildings. Distributing circuits operating at 6600 volts are now quite common. There are also a few 10,000-volt, and a small number of 15,000-volt, distributing systems using outdoor transformers.

Thus far, about 50 kilovolt-amperes has been the limiting capacity found in outdoor service, but there are a few exceptions. Outdoor transformers of 100 kilovolt-amperes capacity or greater, for any voltage, have been almost unknown. Recently, however, large transformers have been taken up; a few are in service, and most of them but for a short time.

The outdoor problem may be divided into two parts:

1. The production of satisfactory outdoor apparatus.
2. The application of outdoor apparatus.

The design and construction will be discussed, and the application will be considered.

Construction. Transformers for outdoor service may be built for any requirements that the ordinary indoor type of oil-insulated unit will satisfy. As to capacity, the limit of approximately 500 kilovolt-amperes will apply to the self-cooled type, depending somewhat on voltage and frequency. As with the self-cooled indoor transformers, the case is the principal problem. It is difficult to obtain the radiating surface required for cooling very large transformers, and still retain a simple mechanical construction. Oil-insulated, water-cooled, outdoor transformers can be built for any capacity irrespective of voltage and frequency.

The first problem apparent in the development of outdoor transformers concerned the terminals: how to make them reliable in all kinds of weather and service. The next problem was to weatherproof the case satisfactorily. This much of the problem has been worked out, and now outdoor transformers up to 500 kilovolt-amperes capacity have been built, and units for potentials up to 60,000 volts are in service.

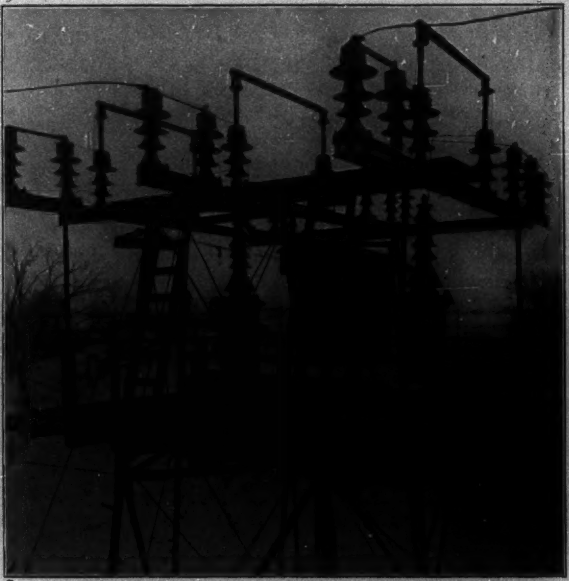

FIG. 1—Two 60,000-volt outdoor series transformers.

The downward projecting lead which issues from an overhanging pocket near the top of the transformer case is a quite satisfactory construction for moderate potentials. 10,000 volts or more can better be carried by upward projecting terminals, this arrangement being particularly attractive for convenience in wiring. About the same practice for placing outlet terminals serves for both indoor and outdoor transformers, so far as the general arrangement and convenience are concerned. The essential requirements of outdoor terminals are that they retain their insulation characteristics and that they do not deteriorate by exposure to the elements. Outdoor terminals are larger and require much more room than those for indoor service.

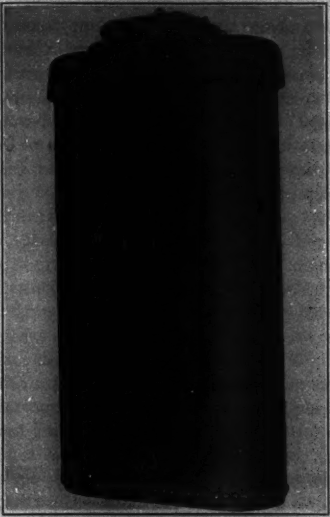

Fig. 2—This construction for outdoor service has been used for 6600-volt 25-cycle, three-phase transformers from 75 to 350 kilovolt-amperes.

Fig. 11 illustrates a self-cooled, 300-kilovolt-ampere, 33,000-volt, outdoor unit. The case is of corrugated sheet-iron with welded vertical seams. The bottom and top are cast on the corrugated shell. The resulting construction is strong, oil-tight, and is not subject to damage by the elements. The cover, also of cast iron, has a considerable overhang or eave to guard the joint between it and the top of the case, and is fitted with the outlet terminals and a small inspection door. All joints are protected by an overhang and are designed for making tight with gaskets.

Outdoor water-cooled units employ the same general construction as the self-cooled type, except that the cases will usually be of boiler iron, and cooling coils with connections must be provided.

Weatherproofing outdoor transformer cases is doubtless best done by making the joints vacuum-tight. Eliminating leaks means that nothing can enter, and therefore a clean, dry unit would remain in that condition. Moisture is the only enemy to be feared, either in the form of rain, snow, or humidity. The "breathing" of wet air is the most important source of trouble because it is the hardest to eliminate. As a transformer heats, part of the air in the top of the case will escape if an outlet exists and new air will return as the initial temperature is resumed. Under certain conditions moisture which may have entered with the new air will condense. The amount of moisture which will accumulate in this way, in a short time is quite surprising. Well-made gasket joints, with deep, overhanging eaves and carefully sealed-in outlets, give good results.

Application. Whether outdoor apparatus is really desirable, involves a great many points even after it is proved satisfactory in the individual piece. Some of the more important considerations are: location and climate; cost of building and ground for indoor station; cost of corresponding ground for outdoor station; capacity of station; high-tension and low-tension voltages; number of high-tension and low-tension circuits; method of operation and control; method of cooling; attendance and supervision; instruments and their housing; and the cost of indoor versus outdoor apparatus.

A 20-kilovolt-ampere, 2200- to 220-volt transformer immediately suggests a pole installation. But if the figures are multiplied by ten, a 200-kilovolt-ampere, 22,000- to 2200-volt transformer suggests indoor service. If these figures are multiplied by three, a 600-kilovolt-ampere, 66,000- to 6600-volt transformer certainly has always demanded housing.

The large clearance required for exposed high-tension wiring and disconnecting switches; the expensive construction demanded for enclosed high-tension wiring and switch structures; the cells or compartments often used for transformers; the space for protective apparatus—all these operate to make the high-tension station costly as compared with the low-tension station. If all high-tension apparatus were placed outside, some kind of a structure would still be required in most cases for housing the instruments, the high-tension control apparatus, and the low-tension switchboard. If attendance were contemplated, some additional facilities might also be required. Under nearly all conditions where control of either or both high- and low-tension circuits is demanded, some housing will be required. Attendance, or at least frequent inspection, should usually be provided. When housing is needed for part of the apparatus, perhaps a large part, the expected advantage of placing the remaining apparatus outdoors may not become important, or may even not exist at all. In order to obtain the cost comparison, the cost of the station grounds and indoor apparatus must be balanced not only against the smaller building, but also against all the ground required for the outdoor apparatus, the outdoor apparatus itself, and the instruments and the indoor control apparatus.

If the high-tension circuits are many, and switching is contemplated, the outdoor arrangement appears attractive. If the low-tension plan calls for the control of the several circuits, the indoor arrangement looks desirable, as but little additional indoor space over that required for the instruments and high-tension control panels may be necessary for the low-tension switchboard. Furthermore, indoor low-tension switches and wiring, especially if remote control be not used, should be cheaper. Finally, when there has been provided a house that covers all but the high-tension pieces, it may be found that a small additional cost would have housed everything. Evidently no rule can be set down, as every case will require individual solution.

With all the large bodies of oil in such apparatus as the transformers and circuit-breakers outdoors and only instruments and remote-control boards indoors, the life and property hazard may be considered as less than in the equivalent but more congested indoor arrangement. The likelihood of careful inspection, however, is also much less, especially in bad weather. The difficulty of outdoor repairs except in the finest weather, is worthy of attention; though failures are very infrequent with well-built high-tension apparatus.

The successful outdoor transformer would itself be of less interest if outdoor switches and protective apparatus were not also available. Under such conditions, omitting the housing for the transformer might be of small advantage if protection for all other apparatus were still to be provided. The economy anticipated from employing outdoor transformers can generally be but partly realized without other outdoor apparatus.

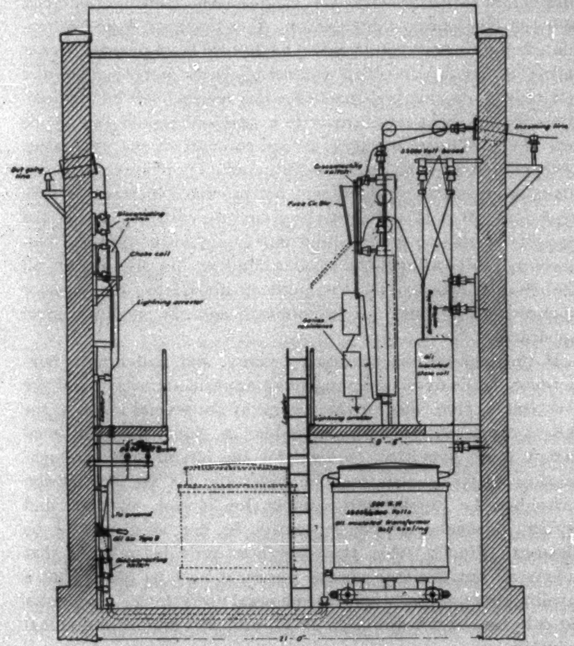
Out going line
Disconnecting switch
Choke coil
Lightning arrester
Incoming line
33000 volt buses
Disconnecting switch
Series resistance
Oil insulated choke coil
Lightning arrester
9'-6"
500 K.W.
33000/6600 Volts
Oil insulated transformer
Self cooling
To ground
Oil Sw Type B
Disconnecting switch
11'-0"

FIG. 3—Sectional view of 1500 kilovolt-ampere, 33,000-volt to 6600-volt, 25-cycle transformer station.

Fig. 3 shows an indoor 33,000-volt station and Fig. 4 shows an equivalent outdoor station, No instruments are employed and no attendance is required. The station is entirely without a building. Fig. 5 shows a 60,000-volt indoor station, and Fig. 6 shows an equivalent outdoor station of one-fourth the capacity. As an example of the growth toward outdoor stations, there may be cited the Lockport station of the Niagara, Lockport & Ontario Power Company. Some of the illustrations of this station showing outdoor lightning arresters and 60,000-volt busbars have already appeared in the Institute TRANSACTIONS.*

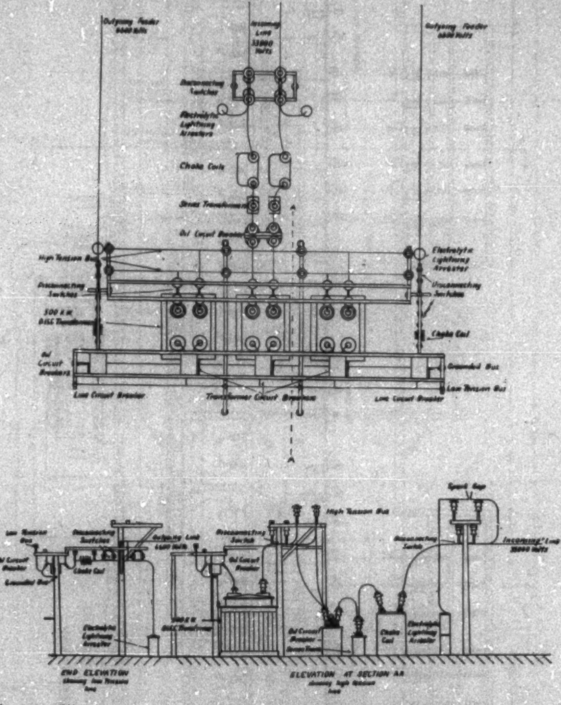
Outgoing Feeder 6600 Volts
Incoming Line 33000 Volts
Outgoing Feeder 6600 Volts
Disconnecting Switches
Electrolytic Lightning Arresters
Choke Coils
Series Transformers
Oil Circuit Breakers
High Tension Bus
Electrolytic Lightning Arrester
Disconnecting Switches
Disconnecting Switches
500 K.W. D.S.C. Transformers
Choke Coil
Oil Circuit Breakers
Grounded Bus
Low Tension Bus
Line Circuit Breaker
Transformer Circuit Breakers
Line Circuit Breaker
A
A
Spark Gap
High Tension Bus
Low Tension Bus
Disconnecting Switches
Outgoing Line 6600 Volts
Disconnecting Switch
Oil Circuit Breaker
Choke Coil
Grounded Bus
Oil Circuit Breaker
Disconnecting Switch
Incoming Line 33000 Volts
Electrolytic Lightning Arrester
500 K.W. D.S.C. Transformer
Oil Circuit Breaker
Series Transformer
Choke Coil
Electrolytic Lightning Arrester
END ELEVATION
Showing Low Tension Bus
ELEVATION AT SECTION AA
Showing High Tension Bus

FIG. 4—Illustrates an outdoor transformer station equivalent to the one shown in Fig. 3.

Considered purely as a circuit-interrupting device, whether

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* Transactions A.I.E.E., 1907, Vol. XXVI, Part II, p. 1273.

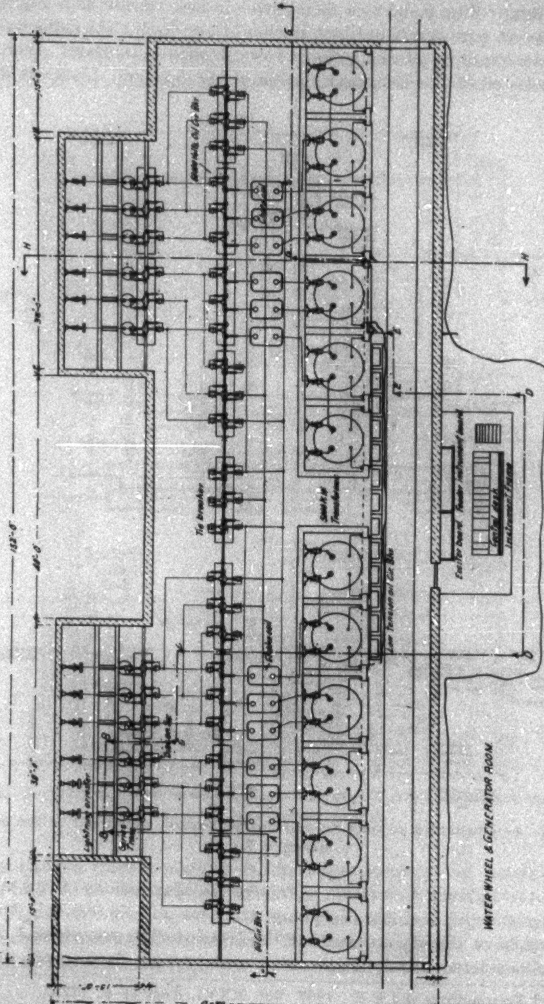

WATER WHEEL & GENERATOR ROOM
Lightning arrester
Series Trans
Oil Cir Bkr
Reactance
Tie breakers
Switch Transformers
Low Tension Oil Cir Bkr
Exciter board
Feeder instrument board
Control desk
Instrument frame
132'-0"
48'-0"
44'-0"
13'-0"
15'-0"
H
D
G

FIG. 5—Plan of 60,000-volt, 60,000-kilovolt-ampere, indoor transformer station.

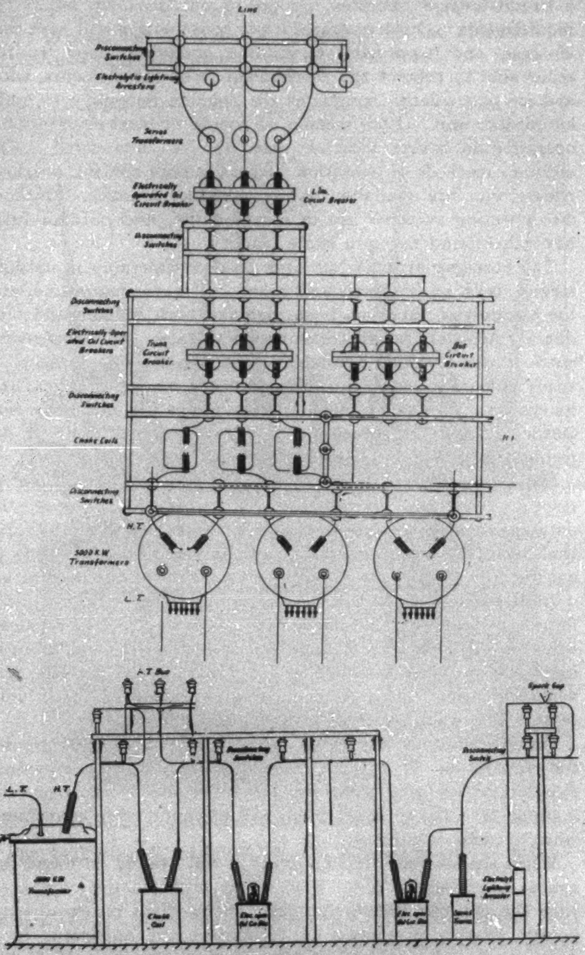

Line
Disconnecting Switches
Electrolytic Lightning Arresters
Series Transformers
Electrically Operated Oil Circuit Breaker
Line Circuit Breaker
Disconnecting Switches
Disconnecting Switches
Electrically Operated Oil Circuit Breakers
Trans Circuit Breaker
Bus Circuit Breaker
Disconnecting Switches
Choke Coils
Disconnecting Switches
H.T.
5000 K.W Transformers
L.T.
H.T Bus
Spark Gap
Disconnecting Switches
Disconnecting Switch
L.T.
H.T.
Transformer
Choke Coil
Electrolytic Lightning Arrester

FIG. 6—Layout for outdoor transformer station, equivalent to one-fourth of indoor station, Fig. 5.

a circuit-breaker operates indoors or out does not affect the requirements. Outdoor transformer construction will take care of case and terminals—a suitable enclosing hood readily removable to protect the mechanism from the elements, snow and ice particularly, completes the changes necessary to make an outdoor unit. Non-freezing oil should be used in order that operation in severe weather may not be endangered. The ordinary methods of operation such as remote control, overload release, etc., are available just as in indoor practice. Outdoor disconnecting switches are in common use, and outdoor fuses have also found favor in some places.

The horn-gap arrester has been used considerably in outdoor service, both at terminals and along the transmission line, and the electrolytic type has been installed both indoors and outdoors. Arresters for all transmission voltages and designed for outdoor use are now available. The considerable amount of space indoors required for high-voltage lightning-arresters, and its cost, are serious; in fact, arrester houses are not unknown. Outdoor types may therefore be of particular and almost independent interest.

Outdoor choke-coils differ from indoor choke-coils only in respect to case and terminals; if of the oil-insulated type, the outdoor-transformer construction will apply. It is noticeable that about the same structural problems and solutions apply to outdoor transformer circuit-breakers and protective apparatus.

It has been suggested that by treating the high-tension transformer as part of the line, no high-tension circuit-breakers would be required and no high-tension lines need enter a building. All switching would be done on the low-tension side, and when necessary fused disconnecting switches on the high-tension side would serve to cut off the transformer.

Outdoor stations should be paved and well drained around the apparatus. If this is considered too costly, individual foundations for each piece will serve. Transfer trackage with a truck, or a heavy hand truck will be found very convenient when moving apparatus.

When the stations are important it will usually be found desirable to arrange a room with repair facilities and connected with the outdoor station trackage, rather than resort to temporary weather protection or to remove the apparatus to a distance, should repairs be necessary. Such space would doubtless be convenient for many purposes such as cleaning and inspecting. Fencing, to keep out intruders, is advised when more than the bus-bars are outdoors.

The general use of outdoor apparatus to the exclusion of indoor apparatus is, of course, not to be expected; but frequent applications will doubtless be made as a development of the general type of station just referred to. Transformer and switching stations present the greatest opportunities, as power houses and sub-stations employing synchronous converters or

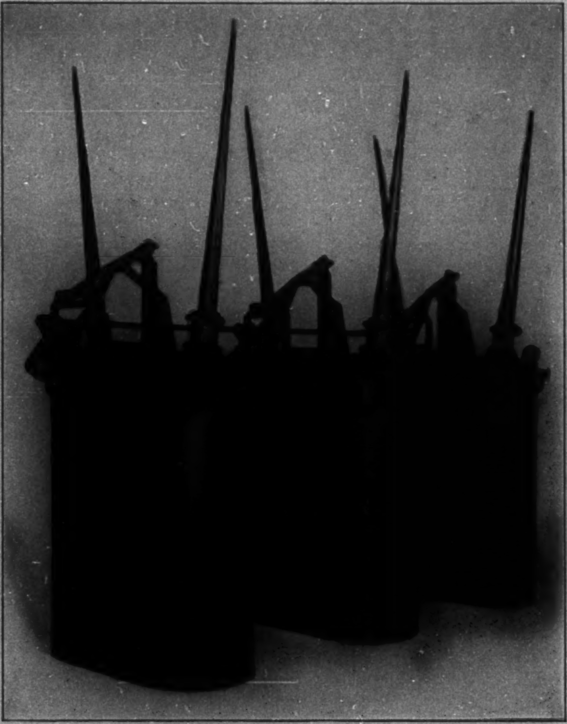


FIG. 7—Three-pole indoor, 60,000-volt, 300-ampere circuit-breaker.

motor-generator sets require so much housing that indoor transformers, circuit-breakers, etc., may be considered best.

If power is to be used within a short distance of a transmission line, a single transformation to the service voltage will be best. When an extended distribution is to be fed, a secondary transformation to the service voltage should be employed. The outdoor transformer will serve in either place, but with existing primary transformations the smaller secondary transformation affords a particularly attractive field.

Costs. Outdoor transformers, like the indoor type, increase in cost as the operating voltage is raised, and decrease in cost as the frequency of operation is increased. It is common to prefer a few large transformers rather than several small units. Also large transformers for the transformation from the high transmission voltage, with several smaller units on a secondary system, are preferred to a number of small units serving the consumers by one transformation from the transmission voltage.

The following cost estimates based on existing installations—two equivalent indoor and outdoor 2000-kilovolt-ampere, 25,000-volt, 60-cycle stations—may be of interest.

Indoor station. High-tension apparatus inside of building. Transformers in pockets.

Approximate cost of steel building. frame erected	$3100
Inside of building, including steel work	2300
Total for building	$5400
Two 1000 kilovolt-ampere, three-phase, 22,000-volt to 440-volt, 60-cycle transformers delivered and erected	7200
Switchboard for above, including two incoming line panels step-down transformers' panel, and necessary oil switches	2500
Total for station	$15,100

Outdoor station.

Building, including outside bus-bar structure	$1020
Two 1000 kilovolt-ampere outdoor transformers as above, delivered and erected	7800
Switchboard as above (only low-tension apparatus and panels inside) all high-tension bus-bars and transformers outside, delivered and erected	2625
Total for station	$11,445

From these figures, the indoor station costs approximately 30 per cent more than the outdoor station.

Another example covers the approximate costs of a 3000-

kilovolt-ampere, 22,000-3000-volt, 25-cycle motor-generator sub-station.

Indoor station. Incoming lines 22,000 volts, two of which are installed. Building structural steel, all apparatus inside, transformers in brick compartments. High- and low-tension bus-bars and oil switches in compartments.

Length of building 110 ft., width 38 ft., equalling 4180 sq. ft.	
Approximate cost of building ready for apparatus, steel work and compartments	$21,835
Three 1000-kilovolt-ampere, three-phase, 22,000/3000 volt, 25-cycle, step-down transformers, delivered and erected	15,000
Three 1000-kilovolt-ampere, motor-generator sets, motor synchronous type, 3000 volts operating at 80 per cent leading power-factor. Generator 550/600 volts, delivered and erected	48,000
Three 45-kw. exciters, induction motor driven, delivered and erected	4,500
Two incoming lines 22,000 volts, three-phase.	
Three three-phase 1500-kilovolt-ampere, step-down transformers panels 22,000/3000 volts.	
Two three-phase railway feeder panels 3000 volts, 3000 kilovolt-amperes.	
Four three-phase lighting feeder panels, 3000 volts, 500 kilovolt-amperes.	
Three panels for controlling motor-driven exciters.	
Three synchronous motor panels.	
One direct-current feeder and total output panel 600 volts, 3000-kilowatt switchboard delivered and erected	20,000

Recapitulation.

Building	$21,835
Switchboard	20,000
Transformers	15,000
Motor-generator sets	48,000
Exciters	4,500
Total cost	$109,335

Outdoor station. High-tension apparatus outdoors on concrete foundations. Building to be 110 ft. by 19 ft. Station same as above as regards output. Ordinary type of building. No steel work.

Building	$7,480
Switchboard, same as above. Oil switches made weatherproof	20,200
Transformers made weatherproof	16,000
Motor-generator sets as above	48,000
Exciters, as above	4,500
Total	$96,180

In this example, as might be expected, the saving of approximately 13 per cent is not so large as for the simple transformer station.

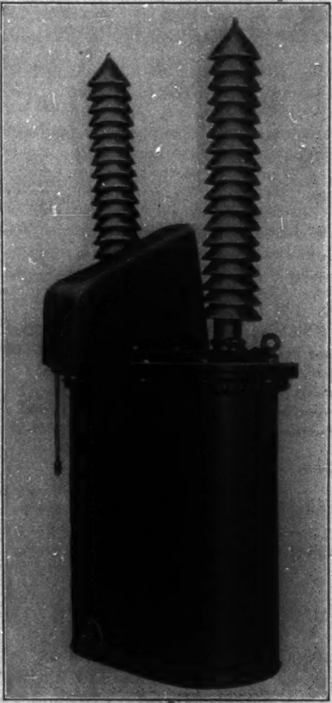


FIG. 8—Single-pole, 60,000-volt, 300-ampere, outdoor breaker. (This is one pole of three-pole indoor breaker, Fig. 7, arranged for outdoor service).

Service. For outdoor transformers the same care is required as for indoor transformers. An occasional test of the oil as obtained from the sampling pet-cock should be made. If attendance is at hand the usual load and temperature log should be kept. This applies to self-cooled and water-cooled units just as in indoor practice. Thorough and detailed inspections should be made at such infrequent intervals as the operating conditions would indicate to be desirable.

In the summer, protection from the sun will probably be an advantage, and this may take the form of a simple fence high enough and so placed as to cast a shadow over the transformer during the hottest hours of the day. At night the cooling conditions will be much more favorable, and the heat accumulated during the day will be discharged, so that each day is started with a cool transformer. The large amount of oil in self-cooled transformers represents a great thermal capacity; it acts as a sort of flywheel for the system, tending to smooth out temperature fluctuations.

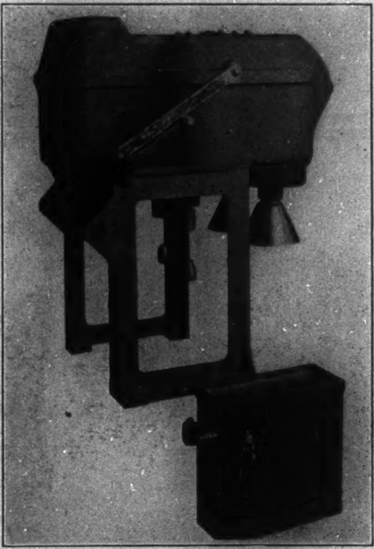


Fig. 9—11,000-volt, 300-ampere, remote-control, automatic, outdoor circuit-breaker.

Water-cooled units do not require shade, and if attendance is at hand their temperature can be held practically constant under varying load and weather conditions, if desired, even without automatic thermostatic control of the cooling water.

In extreme winter weather, if the transformer is likely to be shut down for a considerable time the cooling coils should be freed of water so that they cannot freeze and burst.

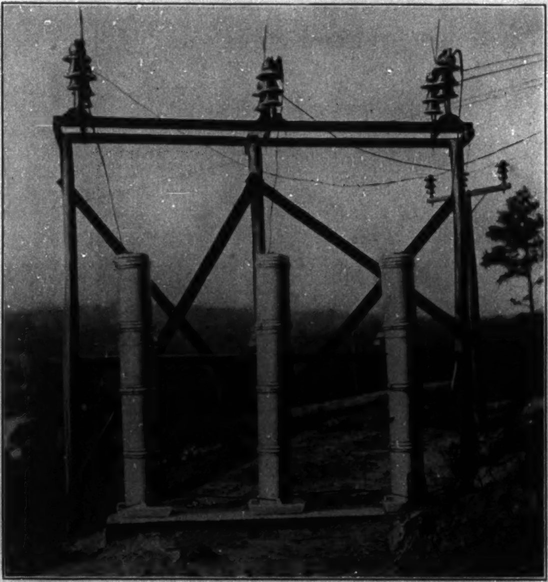


FIG. 10—Outdoor installation of 50,000-volt, electrolytic lightning-arresters.

Transformer oil will thicken at about 0° cent., but does not harden so as to damage windings or case, as freezing water might do. When cold as this the insulating quality of the oil is reduced, but not so as to make it unfit for its purpose. In ordinary service such conditions need not arise, as the iron loss alone will usually suffice to keep the oil fluid. In extreme weather conditions, self-cooled units may be kept warm by screening with a tarpaulin, thus reducing the effectiveness of the cooling surface. Similarly, the water-cooled unit may be operated without water, or with very little, to accomplish the same results. In some instances it may be found desirable to lag the water supply pipes during cold weather.

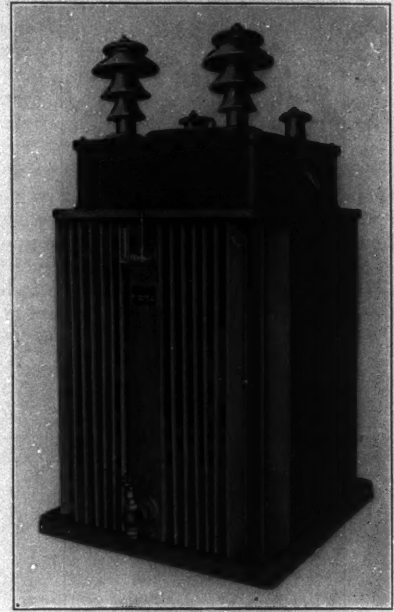


Fig. 11—300-kilovolt-ampere, 33,000/6600-volt, 60-cycle, oil-insulated, self-cooled transformer. (Illustrates general construction for outdoor transformers of moderate capacity).

A self-contained sub-station made up of transformers, circuit-breakers, and choke-coils has been proposed. Such an arrangement, if three-phase, would require but three high-tension leads and would dispense with of twelve other leads otherwise required by switches and the choke-coils. If the choke-coils are omitted, six leads are still saved. For capacities up to approximately 250 kilovolt-amperes this arrangement may be found attractive. Such units should be protected by fuses or other circuit-interrupting devices on the high-tension side, as a failure outside of the switch could not be relieved by it. Disconnecting switches should also be used.

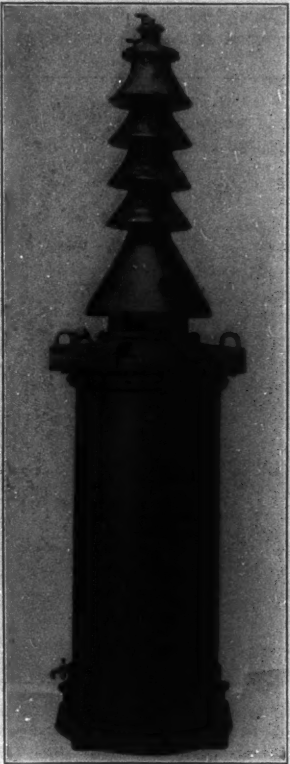
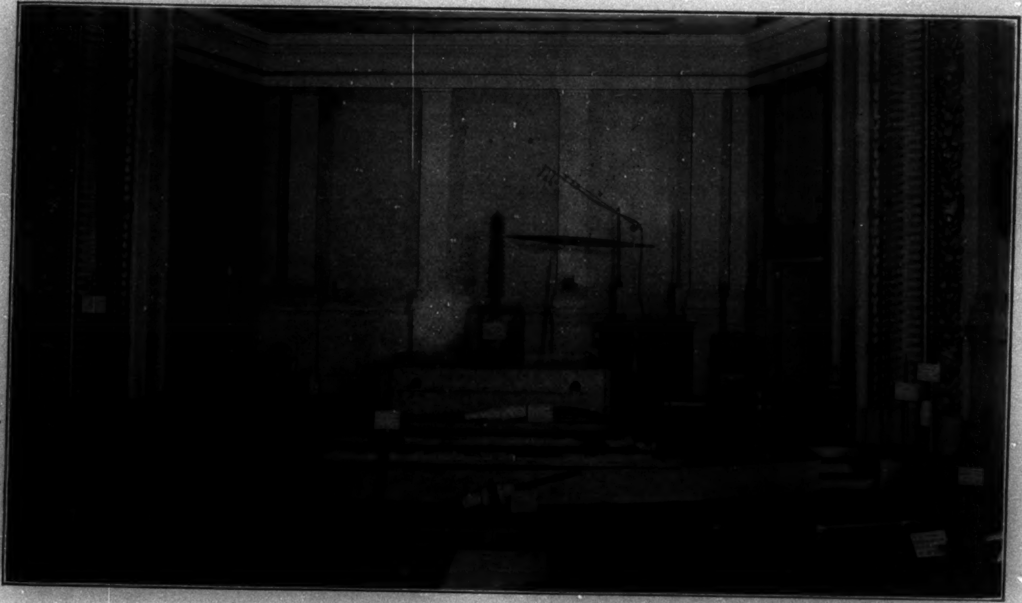


FIG. 12—60,000-volt, outdoor series transformer. (Fig. 1 shows two of these transformers installed).

A construction which permits of shipment in the case with oil is an improvement in transformer design which has been received with quite general favor, as the installation problem is much simplified. The usual unpacking, reassembling, and drying out, if necessary, is reduced simply to removing the blind flanges from the terminal openings and replacing the terminals in order to be ready for operation. Transformers arranged for shipment in their cases with oil, if made weatherproof, need never enter a building after leaving the factory, unless repairs or inspection should demand it.

Summary. The advantage of outdoor apparatus lies in cheapening the installation, due to a saving in building; there is also less life and property hazard. The disadvantages are absence of protection from weather when inspecting, overhauling or making repairs, and exposure to molestors. The problem, as a whole, was, first the transformer; second, the switch; and, third, the protective apparatus. All of these have been worked out and some experience obtained. The problem now is to decide when outdoor apparatus is warranted. This is a question of the station rather than the apparatus, and is subject to the individual conditions of each case.



Apparatus used for testing condenser type of insulation for high-tension terminals to 225,000 volts
Auditorium of the Engineers' Building, New York, April 9, 1909.

A paper presented at the 236th meeting of the American Institute of Electrical Engineers, New York, April 9, 1909

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CONDENSER TYPE OF INSULATION FOR HIGH-TENSION TERMINALS

BY A. B. REYNDERS

The manufacture of apparatus for pressures of 88,000 volts or more resolves itself into the proper selection and arrangement of insulating materials. Of all the problems involved in this selection and arrangement, that of insulating the terminal wires where they pass through the case presents the greatest difficulty. When the terminal wires are carried through a metal cover the danger from breakdown is increased, yet the tendency of the latest designs is toward the use of metal tanks and covers. Even with present voltages the greatest difficulty lies in bringing out the terminal wires through the case. What may be termed "brute force" has characterized the proportioning of high-tension terminals up to the present time, as almost every class of insulating material in nearly every possible shape has been used to surround the conductor as it passes through the top of the case. The top itself has often been made of insulating material such as wood, simply to assist in insulating the lead.

One convenient way of analyzing the terminal problem is to consider it as a short piece of cable. The failure of such a terminal can occur in two ways; namely, by a puncture through the insulating material separating the inside conductor from the outside conductor or support, or by "creeping" over the surface from the end of the inside conductor to the end of the outside support.

Jona in an article on "Insulating Materials in High-Tension Cables" read before the International Congress at St. Louis in 1904, shows how the distribution of stress varies throughout the dielectric, being inversely proportional to the radius. Furthermore, he shows that by grading the material according to its specific inductive capacity, it is possible to make the stresses nearly uniform throughout the dielectric.

Fig. 1 shows graphically the distribution of potential in an insulated cable for a homogeneous material. The ideal condition is obtained when the distribution lies in a straight line.

By the introduction of layers of different materials with specific inductive capacities decreasing from the center outward, Jona obtains the result approximately as shown in Fig. 2, line *A C*. The curve *A B* is the same as in Fig. 1. By this method failure due to puncture in a properly designed cable is practically eliminated, but if the use of a piece of such a cable as the outlet lead from a transformer or a circuit-breaker is attempted, the greatest difficulty would be from breakdowns over the surface by "creepage" from the support to the ends.

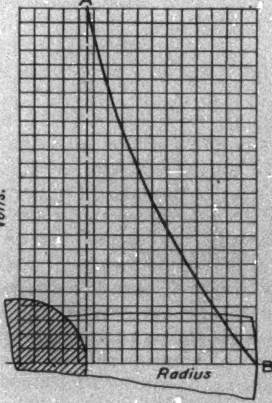


FIG. 1—Cable with homogeneous insulation: distribution of potential through dielectric.

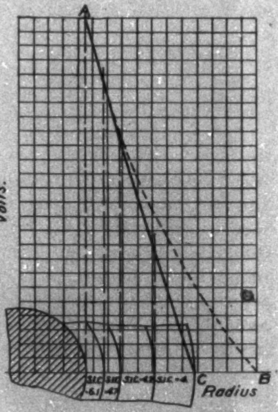


FIG. 2—Cable with graded insulation; distribution of potential through dielectric.

A method that takes care of both puncture and creepage has been proposed by Ryan, Smith, Nagel, and others. This method consists in dividing the dielectric by means of metal plates into a series of condensers of fixed capacities; for it is a known fact that if a difference of potential is impressed across a number of condensers connected in series, each will take its share of the stress in inverse proportion to its capacity. This principle has been utilized in constructing a terminal consisting of a small center rod or tube just large enough to carry the current, the rod being surrounded by alternative concentric cylinders of insulation and metal having the ends tapered in steps as shown in Fig. 3. The distribution of stress through the dielectric owing to the metal layers has been changed from a curve as shown in Fig. 1 to a straight line as shown in Fig. 2. Furthermore, the ends of the metal layers fix the distribution of voltage over the surface, which thus can be kept within safe limits. This design may be designated as a condenser type of terminal.

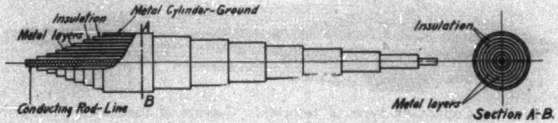


FIG. 3—Condenser type of terminal.

Before considering the mechanical design of this type of insulated terminal, it would be well to dwell on a few fundamental facts that will limit the design. It is obvious that in order to obtain the maximum efficiency from the insulating material every part of it should be subjected to a stress proportional to its strength. Further, if the dielectric material is homogeneous throughout, every particle should be strained the same as every other particle. This means that in a series of condensers employing a homogeneous dielectric throughout, each one should have the same capacity and the same thickness as every other one. In order to obtain this desirable result various difficulties must be overcome. It is the purpose of the following to show how this can be done.

The formula for the capacity of two concentric cylinders is:

$$C = \frac{k\,l}{2 \log \frac{r_2}{r_1}}$$

where

C = capacity in electrostatic units

k = specific inductive capacity of the dielectric.

l = length in centimeters of the conducting cylinders.

$r_1 - r_2$ = radius in centimeters of the inside and the outside conducting cylinders, respectively.

A glance at this formula shows that the capacity may be varied by changing the thickness between the conducting cylinders, the length of the conducting cylinders, or the specific inductive capacity of the dielectric.

It is now very generally known that the dielectric strength of ordinary solid insulating material does not increase proportionally as the thickness is increased. For this reason it is evident that varying the distance between the cylinders in order to obtain equal capacities will cause some layers to be thicker than others, and hence there is a waste of material.

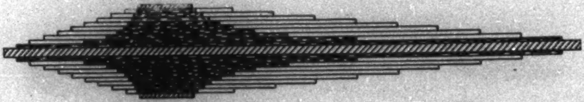


Fig. 4—Condenser type of terminal. Layers of insulation of equal thickness. Shaded portions show equal capacities throughout. Full lines show equal capacities on inside and outside layers and capacities, increasing towards center of insulation thickness.

The second method of varying the capacity—by changing the length of the conducting cylinder—is determined approximately, when equal capacities in all condensers are desired, by making the surface area, or the product of the length by the diameter, equal for all conducting cylinders. When the diameters of adjacent layers are nearly equal—a condition approached as the diameters increase—and the thickness of insulation remains constant, the ends of the layers come very close together, and failure is liable to occur by creepage. In other words, the most economical design for creepage is to make equal steps with an equa difference of potential between the ends of each step. This cannot be accomplished by varying the areas alone, as shown by reference to Fig. 4. The shaded portion shows the shape which the ends must have for equal areas, while the full straight lines show the shape the ends must have if equal steps between layers are obtained. The best compromise that can be obtained is to make the inside area and outside area equal and to allow all others to vary. The result is that the stresses are greatest at the center and on the outside, and decrease toward the middle.

The third means for obtaining equal capacity is limited by the variation in the specific inductive capacity of the available insulating materials. Unfortunately the available materials suitable for the manufacture of these terminals have very little variation in specific inductive capacity.

It is, however, by the combination of this third method with the best arrangement secured by the second method, that makes it possible to produce a terminal having equal distances and equal voltages between steps, and thus obtain the maximum economy from the minimum amount of material.

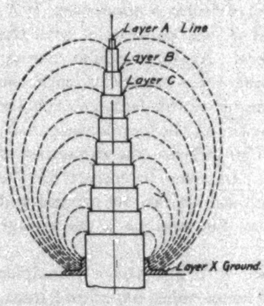


Fig. 5—Static field about condenser type of terminal.

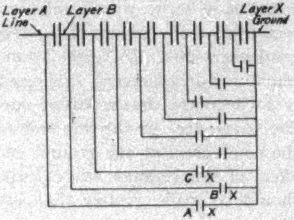


Fig. 6—Diagrammatic arrangement of condensers equivalent to Fig. 5.

In all of the foregoing, only the capacity of the various metal plates with reference to each other has been considered, and it has been shown how it is possible to obtain equal capacities combined with other desirable features. If results on tests are to agree with previous calculations, there is one disturbing element which must be taken into account, especially at the higher voltages. This element is the capacity which each metal layer has to ground.

Fig. 5 shows in dotted lines what is possibly the static field surrounding a condenser type of terminal under service conditions. Fig. 6 shows an equivalent arrangement of condensers in which condensers *A-X*, *B-X*, etc., in parallel with portions of the main series, replace the leakages shown by dotted lines in Fig. 5.

Referring to these figures, layers *A* and *B*, with dielectric material between, form a condenser which will be called condenser *A-B*. In addition, layer *A*, and the outside grounded layer *X*, with the intermediate air or oil as a dielectric, form a condenser, *A X*, which is in multiple with the remaining system of condensers. The only effect of this condenser is to cause corona at the edges of the center rod; that is, if the stress to ground is great enough. To reduce this corona to a minimum, all corners should be rounded, as will be explained later.

In a like manner, layer *B* and the grounded layer *X*, with the intervening medium as a dielectric, form a condenser, *B-X*, which is in series with condenser *A-B*, and in parallel with the remaining arrangement of condensers. Again, in similar manner condensers *B-X*, *D-X*, etc., combine their capacities with the remaining arrangement. The net result of this leakage capacity is to decrease the apparent capacity of the condensers *A-B*, *B-C*, *C-D*, etc., at the line end and to increase the capacities of the condensers at the ground end. In order to correct for the effect of this leakage, the calculated stresses at the ground end should be made greater than at the line end by a percentage determined by experience.

Terminals designed in accordance with the above principles are constructed by rolling up on a metal tube, paper and mica, or paper alone, using as a bond some material like shellac. At regular increases by steps in diameter, for example $\frac{1}{16}$ in., a layer of tinfoil, making one complete turn, is inserted during the rolling process. Great care must be exercised to obtain accurate diameters, especially when the thickness of insulation is small. No air spaces or wrinkling of the paper are allowable, or poor results will inevitably follow. After being completely wound, the tube is placed in an ordinary engine lathe and the ends tapered in steps, the amount of taper depending on whether the end is immersed in oil or surrounded by air. During this turning process careful work is necessary to prevent the turning tool from " digging " into the insulation below the tinfoil, owing to concentric layers of insulation being irregular in shape instead of true circles. After the turning process is completed, the entire terminal should be treated with some insulating varnish in order to prevent the absorption of oil into that portion projecting into the oil, and the absorption of moisture in that portion which is in air.

With a terminal constructed by the above method, there yet remains one point of weakness; namely, the edges of the tinfoil are sharp, and the potential which exists between these edges and ground may be high enough to cause corona effects in the surrounding medium. If this medium is air the result of corona will be the formation of nitrous acid or ozone, which may cause a deterioration of the insulating material and an ultimate breakdown. Up to the present time no harmful effects are known on insulation from corona in oil.

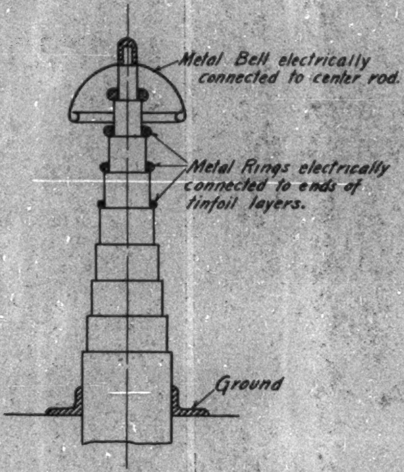

Metal Bell electrically connected to center rod.
Metal Rings electrically connected to ends of tinfoil layers.
Ground

FIG. 7—Arrangement for preventing corona at edges of tinfoil layers.

It is virtually impossible to roll up a tube of insulating paper and tinfoil and obtain all layers concentric and true circles. This will be strikingly shown if the ends are tapered in a straight line. Moreover, with such ends, the tinfoil, which is usually of a maximum thickness of 0.0045 in., is drawn out to a sharp edge and hence the formation of corona by the breaking down of the air in contact with these edges is vastly increased. Again it will be found that there is no fixed surface distance between

Fig. 8—Bulk type of terminal, breakdown 110,000 volts. First evidence of distress, 78,000 volts.

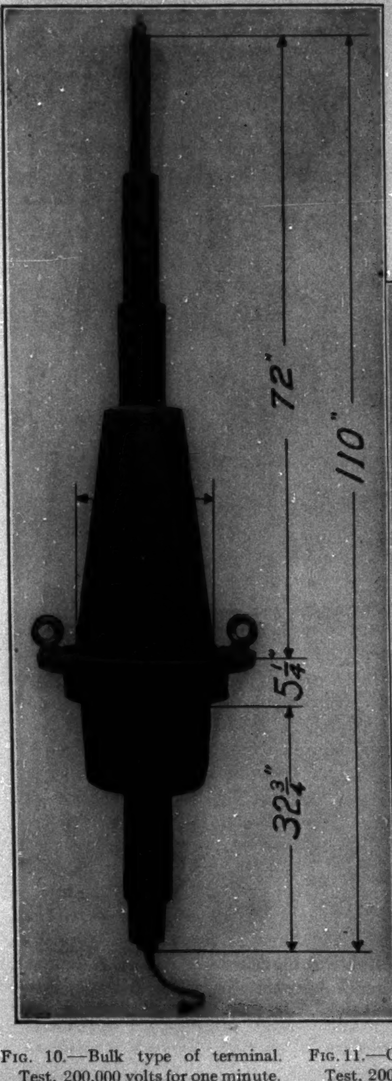
Fig. 9—Condenser type of terminal, breakdown 225,000 volts. First evidence of distress, 200,000 volts.

the ends of the tinfoil layers, due to variations in the insulation between them. For these reasons these ends are always stepped instead of being in one straight line. Even with stepped ends, it has been found that with extremely high voltages, 250,000 and more, the tin-foil edges are sharp enough to cause the formation of corona. As shown by Jona, Ryan, Berg, and others, corona occurs when the stress on the small layer of air at the surface (edge of tinfoil) exceeds the maximum stress which the air will stand. The remedy for such a condition is to make the radius of the end of the tinfoil layer large enough to reduce the surface stress to safe limits. By referring to Fig. 7 it will be noted that this result is accomplished by adding a metal ring of suitable diameter at the corners where the tinfoil ends. This ring is electrically connected to the tinfoil. Furthermore, the addition of a metal bell of large diameter on the central rod at the top not only reduces corona from this rod, but acts as a shield or guard ring for the first few layers, with a resulting appreciable gain in the creepage strength of these layers.

Figs. 8 and 9 show photographs of two terminals under dielectric stress near their breaking point. Both are of the same dimensions throughout. Fig. 8 is the ordinary solid homogeneous type, while Fig. 9 is the condenser type using the same dielectric material as Fig. 8. The stress on the terminal Fig. 8 is 105,000 volts, while that on the terminal Fig. 9 is 200,000 volts. An examination of Fig. 9 shows no flashes on the lower five layers. This is due to these five layers being short-circuited in order to cause the remaining part of the terminal to flash at 200,000 volts, this being the only testing voltage available at that time. If these layers had not been short-circuited, the terminal would not have flashed at less than 225,000 volts.

Figs. 10 and 11 show two terminals designed for the same test of 200,000 volts for 1 minute. The dimensions will show the saving effected in using the condenser type of insulation.

The question naturally arises: If this style of insulation is effective for terminals, why could it not be used for the insulation throughout the transformer? The terminal proposition is one of concentric cylinders, and, if the particular insulation in the transformer is of a similar shape, there is no reason whatever why the condenser type should not be used; its effectiveness, however, is less and less as the diameters of the layers become greater, and the difference between diameters becomes less.


72"
110"
5¼"
32¾"

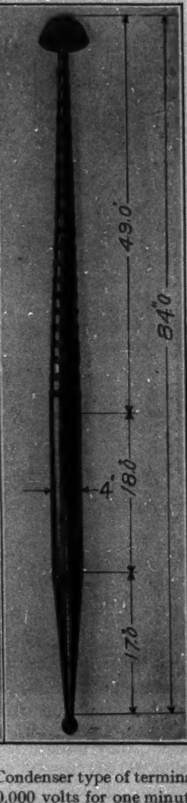

49.0"
84.0"
4"
18.0"
17.0"

Fig. 10.—Bulk type of terminal. Test, 200,000 volts for one minute.

Fig. 11.—Condenser type of terminal. Test, 200,000 volts for one minute.

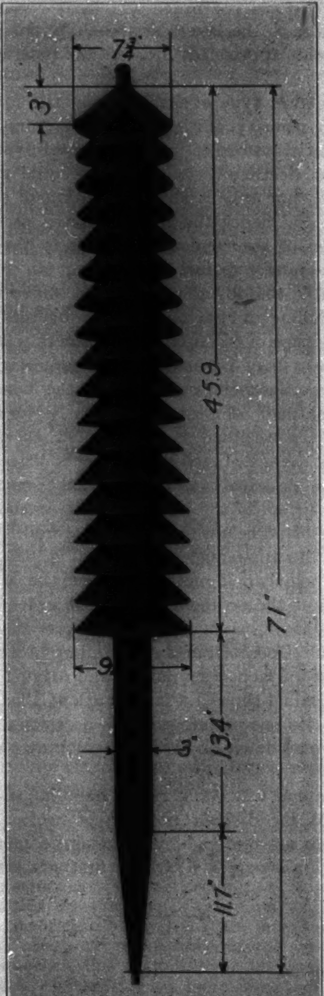


FIG. 12—Outdoor type of condenser terminal. Rain test: first spark 125,000 volts; intact at 150,000 volts, 1 minute; breakdown 200,000 volts.

In other words, as the layers approach a flat surface the potential gradient approaches nearer and nearer to a straight line.

If the condenser type of insulation in the form of a tube is used between primary and secondary or primary and ground in a core-type transformer and the metal layers in the tube are connected electrically to points of equal potential in the windings, then not only is the distribution of stress in the dielectric fixed and hence the total dielectric strength increased, but the action of the condensers assists in the suppression of surges due to outside disturbances.

It is probable that by the use of the above method of connecting the winding and the metal layers together, and the use of the condenser type of terminal, transformers of 300,000, 400,000, or 500.000 volts may be made on a commercial basis.

There is yet another possibility of the condenser type of terminal which may be mentioned; namely. its use for outdoor service. Such a terminal is constructed as mentioned above except that at the end of each metal layer is placed a bell-shaped metal cap in electrical contact with the metal layer. The space on the surface of the terminal between the caps is covered by a cylinder of porcelain or similar material. The completed terminal has the appearance shown in Fig. 12. This terminal without the bell-shaped metal caps has the same dimensions and materials as the terminal shown in Fig. 9 The metal caps vary in size, having a maximum diameter of 9.25 in. and a depth of 3 in. Upon test in a rain, falling at a rate of between 0.2 and 0.3 of an inch per minute, and driving horizontally at times, this terminal showed a faint spark at 125,000 volts, stood 150,000 volts for one minute with an occasional flash between caps. and broke down at 200,000 volts at the end of a few seconds.

Such a terminal will stand rough handling and will solve to a great extent the difficult problem of broken insulators. If the metal discs are replaced by porcelain, a gain will be made in the insulation strength, although first cost and maintenance will be greatly increased.

DISCUSSION ON "HIGH-VOLTAGE TRANSFORMERS AND PROTECTIVE AND CONTROLLING APPARATUS FOR OUTDOOR INSTALLATION," AND "CONDENSER TYPE OF INSULATION FOR HIGH-TENSION TERMINALS." NEW YORK, APRIL 9, 1909

W. S. Moody: Some years ago I attempted to build leads such as described by Mr. Reynders. I found that the difficulties encountered, without the special facilities which have evidently been developed for building the lead before us, made it virtually impossible to gain anything by using this construction.

There is one feature of such a lead that requires more or better insulating material when the condenser cylinders are introduced than when they are not. With the condenser plates in place, every weak spot in the insulation is in series with every other weak spot, whereas a lead covered entirely with insulating material is not weakened greatly by any one of its weak spots, because this weak spot will not ordinarily, by the mere law of probabilities, be in series with any other weak spot. It is possible then that the use of condenser plates in such an insulation, and notwithstanding the better distribution of internal strain, will make a lead no more and perhaps less capable of withstanding a given strain than if the condenser plates were not used. But this may be no serious objection, for, as Mr. Reynders says, the problem of obtaining sufficient insulation to withstand the puncture is not difficult.

It would seem, therefore, that by far the greatest value to be obtained from this construction is in the equalization of the strain along the exterior surface of the leads. There would seem to be no question that the practically equal distribution of strain that can be and has been obtained in the lead shown us does require the minimum length of lead to withstand a given voltage, provided one confines himself to a plain cylindrical or conical surface for the exposed part of the terminal.

My rather limited trial of this form of insulation was sufficient to convince me that such a lead would be a difficult one to produce under ordinary manufacturing conditions, and that it would be, when completed, rather a delicate affair mechanically. I therefore turned my attention to other forms, which have given very satisfactory service on operating pressures all the way from 100,000 to 500,000 volts.

Nearly 8 years ago, when only the most courageous were beginning to think of 60,000 volts as a commercial possibility, I gave to my assistant, J. J. Frank, the problem of building a 500,000-volt transformer. In the preliminary tests leading up to the design of this transformer, it was found when an air or oil space was under electrostatic stress that the introduction into this space of several sheets of metal lowered the voltage required to puncture; whereas the introduction of several sheets of insulating material—consisting of something that was inferior to oil or even air as insulation—markedly increased the voltage required to puncture. It was therefore decided to subdivide the oil—which was chosen as the only material to provide satisfactorily against puncture for a pressure such as 500,000 volts—by insulation cylinders rather than by metal cylinders.

In attacking the problem of providing surface insulation for 500,000 volts, it was clearly apparent that the 15 to 18 ft. of such surface that would be required could hardly be attained in a straight line, but that some form of irregular surface, such as that used in line insulators, must be resorted to. These ideas, combined, resulted in the production of a lead about 16 in. in diameter where it passed through its support, and about 80 in. long each side of this support. This lead has been in most frequent use for six years in connection with all sorts of special testing, and has been subjected to from 300,000 to 650,000 volts.

This lead consists of a tube of low-grade insulating material, tapering in diameter both ways from the point at which the lead is to be supported, the tube being filled with a high-grade insulating liquid or semi-liquid compound, such as oil or asphaltum. The tube is made up of sections telescoping into each other slightly, and between the sections are rings of similar material projecting beyond the sections to give very great leakage distance on the surface. In the later forms of these sections the projecting part is made integral with the section, so that the section has the general appearance of the petticoat of a line insulator. After a suitable cement has been placed on them, all the sections are drawn tightly together by the conductor itself, which is a heavy rod or tube. The space between the walls of the tube and the conductor is divided into several sections by thin cylinders of insulating material. The entire air space in the lead is then filled with the insulating compound.

A lead used for 100,000-volt transformers is regularly tested at 200,000 volts, some of the leads having withstood 225,000 volts for 15 or 20 min. The dimensions of one of these leads are, diameter, 7.5 in., length, 39 in.

It would seem, therefore, that the very long leakage surface, which is so easily attained in this construction, enables one to reduce materially the length of the lead to stand a given strain as compared with a lead without the irregular surface but with a most perfect distribution of the strain, and that no excessive diameter has to be used at the point where the lead passes through the cover. My experience is that there is little difficulty in providing space for leads of quite large diameters in such sizes of transformers as are ordinarily built for 100,000 volts and more. It is desirable though to keep the length of the lead above the cover as small as possible, as the transformer is usually the tallest piece of apparatus that goes into the station, and its over-all height has, therefore, often a direct effect on the cost of the station.

It is evident that one or more of the internal insulating cylinders in this construction could be metallic; and if they were metallic the lead could be made to have a somewhat better distribution of the external strains. But as the lead is now little longer than is necessary to provide a safe factor in the air distance from terminal to cover, only a slight reduction of length could result.

It seems to me that if the principle of distributing the strain on a terminal by a condenser is to be applied extensively, a lead of robust mechanical construction with one, or, at the most, two or three, condenser cylinders is more likely of ultimate adoption than one requiring the refinements of manufacturing conditions and delicate handling required by the lead described in the paper. Moreover, for indoor use at least, it will usually be desirable to use a form of lead whose length from terminal to cover is not greatly in excess of the distance which the test voltage will jump in air.

The problem of having a transformer outdoors is not a new one, of course. All the earlier transformers were placed outdoors as are the present small transformers. The only new points to consider in building large units, as Mr. Randall has said, are in taking extra precautions that the transformer be weather-proof, and providing easy means of repairs.

With reference to their being weather-proof, I believe that in the large units, involving so much money, we should never depend on the joints being absolutely tight, because the best made joint is liable to loosen up. I think it would be very much better if the transformer were kept under a slight internal pressure all the time, so that when leaks developed they would be outward rather than inward. A little gas generator could maintain a pressure on top of the transformer, or an auxiliary tank of oil could be used to keep a slight head of oil on the transformer all the time.

There is one difficulty with transformers installed in this way; that is, the insulating qualities of oil at low temperatures. Oil, when frozen, is ordinarily about as good an insulator as when liquid, but just about the freezing point, especially after it has been frozen, its insulating qualities are greatly reduced. It may be necessary to use some new oil, or some new method of refining oil must be worked out before we can be sure that the transformer that is left outdoors in a cold climate may not have its insulating qualities greatly reduced at low temperatures.

Percy H. Thomas: As Mr. Randall has stated, the crux of the matter of the outdoor station is the advantage in cost of plant; in most other respects the arrangement is, perhaps, disadvantageous. Perhaps it is easier to summarize the difficulties than the advantages. Mr. Randall has well pointed out the chief causes and annoyances of failure; the extra operating expense; the difficulty of inspection, which is really a very important one; and the matter of being able to open the transformers and switches at any time. If the climate is at all bad, I think it would preclude the outdoor apparatus. In any such climate as that of New York where there is much sleet and snow and where one would not always open the apparatus and look at it, I think there would be much difficulty experienced.

The question of repairs is also important. Mr. Randall suggested a special repair house. Would not the cost of a repair house justify the additional cost of putting the whole apparatus in a building? The necessity of working in a cold or exposed place makes any repairs much more difficult, and much slower in their execution. These facts must be clearly borne in mind in weighing any saving in first cost that can be made by omitting the building.

I will call attention to the danger of electrolytic arresters freezing. They seem necessary on high-voltage work, and if there is a long cold season the question comes up whether it is safe to have them remain frozen.

Often in high-tension work the transformers indoors are protected from fire by fire-proof cells. If put outdoors without cells, unless they are much more widely separated, the transformers presumably lose most of the advantage of that isolation; or if cells are used the expense will approximate that incurred in the indoor construction. The matter of lighting an open space is a small item which is sometimes lost sight of in outdoor installations.

In the examples Mr. Randall pointed out, the saving by outdoor stations is entirely incommensurate with the amount of risk and difficulty incurred, but I judge that this would not be true in all cases. In the first case the interest at 10 per cent on the excess cost of the housed plant would be $365 a year, which might be exceeded several times by the cost entailed through the increased difficulty in handling one or two cases of trouble. In the other case, with a little larger plant, 10 per cent interest on the increased cost of the housed plant would be about $1,300.

In the terminal described by Mr. Reynders we have an ingenious use of theory to increase the effectiveness of the terminal material. I think there is no doubt about the correctness of the theory, as is shown pretty clearly by the tests we have seen; but there are some difficulties to be borne in mind. Broadly speaking, the thing which is accomplished by this terminal is the favorable determination of the fall of potential along the surface of the bushing. Puncture through the material is relatively easily cared for; but to prevent a concentration of potential locally on the surface of the terminal, when the conductor has a very small diameter, it is necessary to take some precaution. As has been clearly explained, by making use of the fall of potential within the solid material and balancing the area of the small condensers, equal steps on the surface of the terminal are obtained. As the result of this follows a condition which, while theoretically dangerous, very probably will never arise; that is, if the terminal is designed for ordinary commercial frequencies, the larger current of the small condensers formed by the tin-foil, over and above the true surface leakage current, is the important factor in determining the distribution of potential. If, however, the leakage current over the surface or through the terminal itself should be larger than the charging current of the tin-foil condensers, then the fall of potential over the surface would determine the potential between these tin-foil layers, and the potential drop would be relatively much higher on the first few sections.

As far as the surface leakage is able, it will disturb the condition of equal distribution of potential, putting a very high strain on the inner layers. This condition is, fortunately, not likely to be serious. If, however, we should make a direct-current high-potential test, the charging current to these internal condensers would become practically zero, and the potentials would be determined by the leakage current over the surface, in which case the distribution potential would be much disturbed. Fortunately, in the frequencies higher than normal which we are much more likely to have, the effect is the other way and only increases the safety of the terminal itself.

Mr. Moody called attention to the lining up of the weak spots. This is a matter which should have careful consideration. I believe, however, that the uniformity of material is satisfactory in apparatus of this sort, and unless actual trial shows a weakness in this direction, there is not much to be feared. There is another danger, however, in that if a leak, even a small one, does occur between two layers of tin-foil, the current passing through the leak will be very much increased by the presence of the conducting plates, because the full charging current of all the plate will pass through the weak point; whereas if the conducting material were absent, only a very small current would pass through any given weak local path, not passing through the insulation from terminal to terminal.

I am inclined to believe it the part of wisdom not to attempt to pass the high-tension terminals through a transformer top with an opening of small diameter. It would be better to provide a 20-in. opening than to have a terminal passing through an 8-in. opening in the metal cover. The strains and tendency to corona discharge are certainly greatly increased by the close proximity of the ground to the high-tension parts. It would seem that much effort should be made to have the mechanical construction of a larger insulating diaphragm more suitable for supporting the terminal rather than to attempt to find some way of carrying the high potential through a small opening.

If there were time it would be interesting to discuss a number of alternative forms of high-potential terminal. I do not believe the last word has been said on the subject yet, and in closing I call attention to the condition shown in Mr. Reynders' paper—of a very small diameter of conductor in proportion to the outside diameter of the insulation. That ratio emphasizes the tendency to concentration of potential drop in one portion of the insulation. It is perhaps a favorable condition for the shaping of the tin-foil condensers of this particular type of terminal—the condenser terminal—but some other form of terminal having a larger diameter of conductor would, in that very fact, have an advantage, so to speak, over the condenser form, by relieving automatically in quite large measure the tendency to local concentration.

D. B. Rushmore: The reason for the demand for outdoor sub-stations is the desire to keep the original cost low. That, to my mind, is the only advantage that outdoor sub-stations have, so that instead of asking the question "Where can we use these?" it should be "Where must we use them?", for unless financial considerations make it necessary, there seems to be no reason for their use. There certainly is not apparent any engineering advantage in using them.

In certain climates, however, where either of the extremes of heat or cold predominate, it is a question whether or not to put them outdoors. For instance, in the great heat of Arizona there would be a decided question concerning the desirability of installing large transformers outdoors. There not only the temperature rise, but the final temperature reached, is going to determine the life of the insulation. In that climate, lightning-arresters or any other installation must be protected in all possible ways from the heat, not that absorbed by conduction and measured by temperature rise, but the great heat that comes from the direct radiation of the sun.

In the extreme climates in the north the cold to a certain extent will prevent the operation of mechanical devices through the thickening of the oil. As long as everything runs without interruption a great many conditions are possible which are not advisable in emergencies. It is for the emergency condition that a large part of the apparatus and installations have to be designed. Under severe climatic conditions, great difficulty would be met with in taking care of a large installation where most of it is exposed.

The freezing of the electrolyte of lightning-arresters has been a serious problem, and the development of an electrolyte which will not be affected by freezing is the result of several years of experience. An electrolyte has been found which is not affected by freezing, but there is no indication that it is at all helped by that condition. It is, however, undesirable to have the apparatus more exposed than is necessary; for any transmission line now in operation there are a sufficient number of disturbances to make us consider seriously the question of any further exposure of the apparatus. In most of the long high-tension transmissions, and where on a 100,000-volt transmission line a few horse power are taken off, we will be confronted with a serious condition regarding the cost of installation. It is here that perhaps we shall be most strongly forced to consider the outdoor sub-station.

As I watched the experiments to-night, I was reminded of an installation which was worked under good conditions for a few weeks, and was then followed by a breakdown of the insulators. This is simply an example which goes to show that the breakdown of insulation is not an instantaneous one. Wherever we have a brush discharge, there we have the formation of ozone and, under certain conditions, of nitric acid. This is apt to bring about a slow deposit over the insulating material, and in that way, at the end of a certain time, to cause a breakdown of the insulation. While this is an interesting device, which has been considered in other forms before, in the particular cases that I have in mind it does not seem desirable for mechanical reasons.

Paul M. Lincoln: I believe I am not exaggerating in saying that the lead described by Mr Reynders marks the greatest advance in the high-tension art that has been made during recent years. One of the advantages of this lead and one of the most striking exhibits is shown in comparing Figs. 10 and 11. These transformer bushings are made for the same operating voltage. The smaller one—of the condenser type—has a test voltage of 2.5 times normal, while the larger one has a test voltage which is only twice normal.

When this device was first suggested, the lining up of the weak points of the insulation was thought to be a fatal defect; not until after the thing had been tried out thoroughly was it found that this defect was not fatal.

The method of construction is important. The terminals and bushings are made of paper wound up into form under a heavy pressure and a high temperature. The different layers are put together with a bond of shellac which goes into the joint of the rolling paper. The temperature is high enough to melt the shellac as it goes in, insuring a perfect bond between the adjacent layers. By that means a construction is obtained in which weak points are practically eliminated. When finished the tube is virtually a solid mass.

I would take exception to Mr. Moody's intimation that the lead lacks robustness of structure. I think there can be no bushing made which is more robust in its construction than the one shown.

There was one point that was brought out in the rain test which strikingly confirms one of the points brought out by Mr. Reynders. He has indicated that in designing the terminal it was necessary to sacrifice a perfectly even distribution of potential along the terminal, and that the potential was somewhat higher in the middle than at the ends. It was noticeable that when the terminal was flashing over it was mostly the middle condensers which were discharging, with very little discharge at the ends. This fact illustrates one of the points of construction which Mr. Reynders mentioned.

The spark-gap, which is a shunt to the terminal, has been seen under test. The gap is set at 27 in., so that the voltage which was applied to the terminal was fully 250,000 at the time of breakdown, as the spark-gap was in continual discharge.

E. M. Hewlett: I have been interesting myself for some time in the development of Mr. Frank's oil- or asphaltum-filled insulator which is now being used with high-voltage transformers. I hardly see the necessity of a complicated design when the same result can be accomplished in a simple way.

The bushing of this insulator consists of a built-up shell of insulating material which is filled with a high-grade insulating liquid or compound, such as oil or asphaltum, with concentric cylinders placed inside of the bushing to distribute the potential. This arrangement results in an insulator having the same arc-over value as the equivalent spark-gap.

Considering storms, accumulation of moisture, general climatic conditions, and the trouble of making repairs, it seems as though the outdoor installation could never be a serious competitor of the protected station. In cold climates it would be necessary to use a special oil for the switches or to heat the oil in order to keep it of the proper viscosity for the satisfactory operation of the oil switches.

S. Piek: Doubt has been expressed as to the reliability of outdoor terminals for high-potential transformers. The Niagara, Lockport & Ontario Power Company has had in permanent operation since October, 1908, six outdoor 60,000-volt series transformers, which have operated most successfully during the severe rain, snow, and sleet conditions of the last winter. On the strength of this performance there is no hesitancy to adopt this type of terminal for outdoor power transformers.

The saving in investment made possible by the use of outdoor transformers would be considerably more than the comparative figure in Mr. Randall's estimate, had the indoor station been provided with the facilities which are considered as arguments in favor of the outdoor installation. For instance, a steel building costing $3100 for housing transformers of 2000-kw capacity would hardly have enough floor room and head room to lift a core out of the transformer bank. A building designed to afford such facilities will cost considerably more, possibly double the figure used in the estimate. Furthermore, no allowance has been made for heating facilities which are essential to permit of repair work in any season of the year.

The outdoor transformer arrangement follows closely the traditional indoor station layout. If the money now spent for choke-coils and lightning-arresters were partly applied to the improvement of the transformer installation, the result might be an almost indestructible transformer, which could be placed at any point on the line without requiring much attention for its maintenance.

The Niagara, Lockport & Ontario Power Company has felt the need of outdoor transformers for a long time, and could probably increase its load immediately by 3000 or 4000 kw. if outdoor 60,000-volt transformers were to be obtained.

Guido Semenza (by letter): It is natural that reaction from any exaggerated condition should itself be exaggerated. The indoor high-tension sub-station has in some instances reached such a high degree of complication with walls, partitions, cells, and conduits, that the general feeling is that things have been pushed beyond the necessary limit. Then we are brought by the reaction to the opposite extreme—no walls and no roof. This new form of sub-station requires very careful investigation, and Mr. Randall is to be thanked for having brought the matter before the Institute in such a clear and impartial manner.

In comparing Fig. 3 with Fig. 4 in Mr. Randall's paper, we are impressed by the simplicity of the outdoor arrangement; but if we consider it well we find that some of the objections pointed out by the author and others cannot be neglected. First of all, I quite agree with Mr. Randall that if a part of the station requires housing, the extra cost for housing the whole will not be of great importance. Measuring instruments and controlling panels will not be improved by rain and summer sun. Nowadays a marked tendency is shown toward being able to read instruments in every part of the plant, so that in many cases the outdoor arrangement would not be feasible.

As Mr. Randall states, outdoor apparatus should not only be water-tight, but also air-tight. I am very doubtful if a perfect condition of air-tightness is possible at the inlets, where substances of a very different coefficient of expansion are used, such as porcelain, mica, iron, copper, and compounds. Apparatus repaired under conditions of rain, mist, or snow are liable to deteriorate, and we do not always find customers inclined to wait for a sunny day before having their current put on again. Outdoor sub-stations are not easily protected from direct lightning strokes.

With reference to insulation, I venture to point out the fact, often observed, that in moist air, when porcelain and iron are in contact, the iron rust gradually penetrates the glazing of the insulator, causing a breakdown after a time.

Mr. Randall figures out the cost of first installation only. This is not sufficient. If we take into account the cost of operation, I fear that the larger liability of breakdown of open-air insulators and terminals, the necessity of frequent repainting, of cleaning off dust and insects, and the more accurate inspection required, will more than offset the lower cost of first installation. Thus I feel inclined to conclude that a fair solution would be to simplify sub-stations by making them more similar to the arrangement shown in Fig. 4, but to cover them with a roof, and wall them in.

Exaggeration in partition walls and cells was justified in the early years of high-tension work when switches were considered a dangerous device; nowadays we have more confidence in them and can do away with excessive protection.

A. E. Kennelly (by letter): The introduction of metallic layers into the substance of a dielectric for improving the distribution of electric stress, has been known and used to some extent in the construction of high-tension induction apparatus. It promises to be of considerable assistance in the construction of high-tension terminals in the manner described in Mr. Reynders' paper. This construction not only establishes equipotential surfaces within the dielectric, with a geometrical distribution which is under the control of the designer, but it also limits the range of influence of an accidental flaw in the dielectric to the distance between adjacent conducting layers in the vicinity. This capability of injecting artificial equipotential surfaces is a fortunate property of alternating-current tensions not possessed by steady, or direct-current tensions.

If a condenser type of high-tension terminal were used on direct-current pressure, and any slight leakage to ground occurred from the layer of tin-foil nearest the central conductor, it would only be a question of time for that layer to sink to ground potential through the leak, and thus bring the entire difference of potential stress on the innermost wall of the dielectric; whereas, with alternating current no such cumulative action can occur, and the influence of external leakage current in adding to internal stresses is only in the proportion of the leakage in current to the total condenser current through the dielectric mass.

One of the problems of aerial transmission insulator design may be regarded as analogous to the problem presented in the design of a condenser type of terminal. That is, the glazed surfaces of the insulator should be disposed in such a manner that when they are temporarily converted by rain water into equipotential surfaces, the stresses on the intervening dielectric layers in the insulator shall not be materially altered, and, in particular, shall not be locally increased to a dangerous intensity.

It is doubtful whether the introduction of concentric cylindrical tin-foil layers into the uniform dielectric of a cable can be of utility beyond limiting the radial influence of flaws in the dielectric; because the equipotential surfaces in such a cable are already concentric cylinders, so that in the absence of flaws the introduction of thin tin-foil changes nothing. When, however, as in transformer terminals, the construction is in three dimensions and the equipotential surfaces are no longer simple concentric cylinders, the insertion of the tin-foil alters and controls the potential distribution.

J. S. Peck (by letter): In reading Mr. Randall's paper, two questions suggest themselves to an engineer somewhat familiar with the conditions governing the use of high-voltage apparatus in Great Britain: 1. Will the Board of Trade and the Home Office approve of an outdoor installation? 2. If they do approve, will not their approval be qualified by the imposition of such measures for the protection of the public and operatives, as would make the cost of the outdoor installation as high or higher than the indoor one? Assuming, however, that such severe restrictions are not imposed, and that, as in America, each engineer has practically a free hand to lay out his system as he sees fit, the question appears to resolve itself into a discussion of the conditions under which an outdoor station may be desirable.

The only real argument in favor of the outdoor high-tension station is its low cost. The argument of reduced fire-risk is of secondary importance, while regarding risk to life there is considerable doubt if the outdoor station is as safe as the indoor one, though there is something to be said on both sides. So far as cost is concerned, it would appear certainly that the outdoor has a considerable advantage over the indoor station, but when one notes the way in which the appearance of the handsome building of the Lockport station of the Niagara, Lockport & Ontario Power Company referred to by the author is disfigured by the forest of poles outside it, the possibility of a compromise is suggested. It may be found that in the long run it will pay to protect transformers, switches, and arresters from the direct action of rain, wind, and snow, by some cheap form of building or shed which will be no more offensive to the aesthetic taste than an outdoor station consisting of a mass of poles, insulators, wires, metal tanks, earthenware jars, and fences for keeping off the sun.

The strongest argument against the outdoor station is the possibility of damage to the apparatus through the absorption of moisture. This applies particularly to the transformers, which, being alternately heated and cooled, tend to breathe out hot air and breathe in cool air, the latter possibly being saturated with moisture. As the author suggests, while it is possible to make the case vacuum tight, this is a difficult and expensive matter; and even if vacuum tight when installed, it is an open question whether the case will remain so. Apparently the transformer case shown in Fig. 11 is not vacuum tight, and it would be interesting to know whether the costs of the outdoor stations given would be increased appreciably by making the transformer cases vacuum tight.

In Europe it is almost common practice to protect all transformers from the weather, even those of small capacity and low voltage. The very low mortality rate of transformers in Europe as compared with those in America, even though built to the same specification, leads to the belief that protection from the weather is an item of considerable importance, which certainly will not grow less as the voltage is increased.

Another danger with the outdoor station where water-cooled transformers are used, is the freezing of the water in the cooling coils in the event of a transformer being cut out of circuit for several hours. It is extremely difficult to remove all water from the coils, and a frozen coil usually means a burst one. When the transformers are placed inside a station, it is usually possible to keep the temperature of the station above freezing point.

Mr. Randall apparently assumes that 500 kw. is about the limiting size for self-cooling transformers, but in Great Britain there are a number of 1000-kw, 20,000-volt, 40-cycle three-phase transformers in operation. There is no reason why 1500 to 2000-kw., 50-cycle units of the self-cooling type should not be made, even without auxiliary cooling tanks.

On account of the relatively heavy expense of terminals for very high voltages, and of the difficulty in making them weatherproof, the advantage of using only one terminal on each transformer becomes more apparent whenever the star connection is used with grounded neutral. It should be noted also that with this system the series transformers may be grouped about the neutral point, so that practically no insulation is required for the terminals or between the high tension and ground. Where it is desired to measure the total output of two or more groups of transformers, the secondaries of the series transformers on the different groups may be parallelled.

As stated previously, it is doubtful whether the outdoor station is ever likely to come into favor in Great Britain on account of the possible objections of the Board of Trade and the Home Office and of the aesthetic feelings of the people, but in America, where the use of outdoor transformers of small size is already universal, the outdoor station seems bound to follow. The only question, then, is to determine the limits of size, voltage, etc., beyond which it is better to house the apparatus which may be damaged by the weather and which it may be desirable to inspect or to cut in and out of service from time to time. What these limits are must be determined by experience.

Ralph D. Mershon: Both the papers presented this evening represent a distinct advance in the art of high-voltage transmission. Mr. Randall's paper especially deals with a subject in which I have been interested for a long while. I believe that eventually outdoor high-voltage apparatus will be the rule rather than the exception. I can well remember the indulgent smile with which I was met on making suggestions along these lines several years ago. Even Mr. Randall himself, who is most ready to consider any suggestion which may appear to contain elements of progress, seemed to have grave doubts as to the possibility of successful outdoor high-voltage apparatus.

There are two suggestions made by Mr. Randall which especially interest me. One of these is that of considering the high-voltage apparatus a part of the transmission line, and switching the apparatus and line as a unit. I think in time this course of procedure will prove desirable in many cases where large amounts of power are to be handled, and the transmission is over long distances. The other suggestion is that of putting all the high-voltage apparatus in one tank, so as to require the minimum number of terminals. This is a matter to which I hope the designers of high-voltage apparatus will give careful attention.

It would be interesting to know from Mr. Randall the minimum temperature at which the oil switch could be operated, in view of the fact that the oil will thicken as the temperature is lowered. It would also be interesting to know as to the possibility of putting the complete oil switch, including the mechanism, inside the transformer tank and, possibly, underneath the oil.

I agree with Mr. Piek that Mr. Randall has not allowed enough for the cost of his buildings. In designing a transformer station it is surprising how the cost runs up, and the various details that have to be taken care of are numerous. The point Mr. Piek made is a very good one; that is, if we have room to handle the transformer in the station we will require more room than Mr. Randall provided.

Mr. Peck raises a point which has always interested me; that is, the fact that in using single-phase transformers with the high-voltage side connected in Y, we need only one high-voltage terminal for each transformer, and that by such a method of connection we may locate our series transformers near the neutral point, thus avoiding the necessity of insulating them for high voltages. If such course be pursued, it seems to me that it might possibly pay to go further and bring a lead out from the high-voltage winding near the neutral connection, from which could be actuated the voltage-measuring instruments and the reverse relays where such are required.

Mr. Peck's suggestion brings to mind another point which has always interested me, and that is the desirability of being able to connect both sides of the transforming apparatus in Y, resulting in the same simplicity on the low-voltage side as that obtained on the high-voltage side. As is well known, we hesitate to follow this course now because of the difficulty met with when the neutrals of generating apparatus are connected. This difficulty is generally assumed to be due to the effects of the third harmonic. It is very desirable that this question be given closer investigation, experimental and theoretical, than it has heretofore received, with a view to overcoming the difficulty if possible.

If separate single-phase transformers are used in three-phase transformation, with both high-voltage and low-voltage windings connected in Y, each transformer and the line cable connected to it may be treated as a single-phase unit; that is, the three-phase transmission circuit may be considered as made up of three single-phase circuits 120 degrees apart, and handled accordingly, so that where the return current through the ground would not be especially objectionable, we might, in cases of emergency, switch out a part or all of the transforming apparatus connected to one line conductor and run for a while on the other two phases. Such a possibility as this would greatly increase the flexibility of a transmission system. In this case our switching apparatus would preferably consist of single-phase switches arranged so that they might be operated as such, or, when desirable, operated simultaneously, thus constituting a three-phase switch. Under such conditions the suggestion made by Mr. Randall, of putting the switch in the same tank with the transformer, becomes very attractive.

Of the many written contributions received, one of them, for the reading of which there is not sufficient time, deals with the idea of locating the high-voltage bus-bars and some of the remainder of the high-voltage apparatus on the roof of such small building as may be required for sheltering the sub-station operator and the switchboard measuring and control apparatus. This is a suggestion which has been made a number of times, but, so far as I know, has never been fully worked out. It opens up a subject worthy of further study, as possibly leading to desirable results in economy, reliability, and safety.

Mr. Reynders' paper is a beautiful exemplification of the application of theory to practice, and the advance which it marks should do much in forwarding high-voltage transmission work through the cheapening of reliable apparatus.*

W. S. Franklin: It has occurred to me that I might briefly consider the accumulation of charge upon a high-voltage transmission line, an accumulation which continuously discharges to ground and which is called the "static discharge" by transmission engineers. The maximum voltage that can be created between a pair of single-phase transmission lines and the ground is equal to $\frac{2\sqrt{2}\,C\,E}{C'}$ where E is the effective alternating voltage between the transmission lines, C is the capacity per unit length of the pair of transmission wires with respect to each other, and C' is the capacity of the pair of transmission wires with respect to earth. Thus, a maximum pressure of 560,000 volts may be built up between a pair of transmission wires and earth when the voltage between wires is 40,000 volts effective, and when C is five times as great as C'.

The theory of this effect, as I have worked it out, is based upon the great mobility of the negative ions in the atmosphere as compared with the positive ions, and indeed the above formula is based upon the assumption that the mobility of the positive ions is negligible in comparison with the mobility of the negative ions.

The building up of an excessively high voltage between a pair of line wires and earth does not depend upon a potential gradient in the atmosphere but, so far as the above formula is concerned, depends solely upon the existence of free ions.

N. J. Neall: There is one curious arrangement shown for the outdoor stations that indicates the persistence of established practice, and that is the lightning-arrester equipment which is placed at one particular end of this group of apparatus. I see no reason whatever why it should be used on only one side of the group, so to say. In fact, let us suppose that these sets represent future practice with very high voltages where the transmission lines will be provided with overhead grounded wires. I observe that we have here no overhead grounded wires for the station. I think it only fitting, however, that we should supply the equipment with a static shield also, but the preparation of that static shield will not be so simple when all the wiring now shown is taken into account. A modification of this—but to some extent begging the question—would be to scatter lightning-arresters throughout the group, just as many as the station would afford.

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* Before the close of the meeting, Mr. Mershon said that the thanks of the Institute were due to the Electrical Testing Laboratories for the loan of the testing apparatus used for experimental purposes at the meeting, and to the New York Edison Company for installing it.

G. Faccioli: The so-called condenser type of transformer terminal has attracted the attention of manufacturers and engineers for years. In May, 1906, the *Elektrische Bahnen und Betriebe* gave a full description of such leads and the complete theory thereof. In that paper, as in the present paper, the terminal is compared to a short piece of cable; but a transformer terminal is under very different conditions from a short cable, and the distribution of the stresses is not the same in both cases. In a transformer lead the inside conductor is much longer than the outside grounded plate, and, therefore, all formulas which apply to cylindrical condensers where the inside and the outside plates are of the same length, do not apply to the case of leads.

A simple experiment shows this clearly. Let us take a rod 45 in. long and 0.25 in. in diameter, and let us put this rod in the center of a metallic cylinder 10 in. in diameter and 2 in. long. We ground the outside cylinder and apply to the rod high potential from the terminal of a transformer whose other terminal is grounded. We find that as soon as we reach 40,000 volts, part of the rod covered by the grounded cylinder glows. This means that at the surface of that portion of the rod the electric stress is higher than the disruptive strength of air.

If we raise the voltage, corona will gradually spread on each side of the center of the rod. If we increase the width of the grounded cylinder, we find that the first part of the rod to glow is always in the center and very short in length, showing that the distribution of the electric field is not uniform, but is the strongest in the center and decreases gradually on either side.

Now let us put a thin copper cylinder 5 in. in diameter and 10 in. long concentric with our rod and the grounded disk. If we test the apparatus, we find that corona appears in the center of the rod at 43,250 volts, which is very little above the 40,000 volts found before. This shows that the introduction of the intermediate concentric cylinder in the electrostatic field has changed its distribution very little. We can conclude from this test that the condenser type of lead must have comparatively small diameters and short steps between adjacent tin-foil layers. A small diameter necessitates an abnormal length of lead, for we know that in order to reduce corona and creepage effects, an increase in diameter is far more efficient than an increase in length.

For instance, the condenser lead illustrated in the paper has a length above ground of 49 in. Successful leads for the same voltage have been built with only 39 in. above ground. Their diameter is, however, 7.75 in. in the center. Such leads do not arc over at 250,000 volts, although their length is 10 in. less than the condenser lead.

The condenser type of lead, however, gives a better distribution of potential on the surface of the lead; in fact the equipotential surfaces are straightened by tin-foil cylinders and tend to relieve the crowding of the voltage near the grounded plate. On the other hand, the mechanical construction is very delicate: the lead has to be built cylindrical and then machined to smaller dimensions, and the metallic cylinders connect in series all air bubbles and other faults which are very apt to occur in this kind of construction.

Furthermore, Mr. Jona, in his article referred to in this paper, brings out the point that the introduction of metallic cylinders in the mass of the insulation decreases the resistance to puncture of the apparatus. He gives the example of a copper wire 4 mm. in diameter, insulated to 8 mm. in diameter, then covered with a thin metallic cylinder, next with 3 mm. more of rubber, and finally with a lead sheath. At 8000 volts the insulation between the small wire and the metallic cylinder is punctured; but if the metallic cylinder is removed the insulation is not punctured up to 15,000 volts. The phenomenon is not clearly understood.

We consider in our calculation the different layers of insulation as independent and subjected to a certain difference of potential from one surface to the other. This view, according to Jona, is probably too "static." The phenomenon of "puncturing" is dynamic, and consists in the flow of a certain amount of energy which cannot reach one layer of insulation without going through the other layers. It seems that the various layers of insulation give a considerable mutual assisting action, which is evidently lost if they are separated by metallic surfaces.

In conclusion, as far as puncturing is concerned, this new lead has no advantage over the bulk type of lead, but the fact that the distribution of potential on its surface is much more favorable makes this lead a very desirable apparatus.

C. L. de Muralt: One point which I should like to emphasize is that in the design of our transformer leads—which are the first part of the power-house equipment in connection with the line—we are working against a constantly decreasing margin of safety. It is comparatively easy to take care of the line working-pressure. Even the excess pressures produced by static charges and high-frequency discharges on the line can be handled. But the very apparatus which annihilates the effect of these outside excess pressures may, in connection with the transformers, produce resonance effects which bring on local excess pressures of magnitudes more and more dangerous the higher the line pressure goes.

Transformer terminals and transformer windings have a certain capacity against ground and a certain self-induction. Lightning-arresters usually have a certain ohmic resistance and a spark-gap of some kind. These, with the ground, form a resonance circuit.

So long as $I R^2 > 4 L$, we are on the safe side and there will be no resonance. If $I R^2 < 4 L$, we will have excess pressures which may easily reach multiples of the working pressure. It is therefore necessary to make the ohmic resistance of the lightning-arrester very high. At the same time this resistance should be as low as possible to handle readily the very large currents produced by the outside excess pressures. We have here two absolutely opposing conditions.

I have worked considerably along this line and I offer a solution which I have found safe for very high pressures. Metallic rods connected to the ground are first insulated and then surrounded by a series of metallic discs. The lowest disc is connected to the ground; there is a gap between every two discs, and the last disc is connected to the line by means of a high resistance and a spark-gap. We thus have a series of spark-gaps and also of capacities. Several such devices are then placed in parallel. Each one has a resistance high enough to prevent resonance. The resistance of the group in multiple is low enough to allow any current —thousands of amperes—to pass to the ground without trouble.

Of course the spark-gaps will not operate all together, as they cannot be thus closely regulated. One starts, and as the excess pressure increases others are brought into service until relief is obtained. By these means we have been able to keep the excess pressures within 10 per cent of the working pressure, thus giving a very large margin of safety to transformer terminals even with very high line pressures.

V. D. Moody: As covered by the summary of Mr. Randall's paper, the problem from the manufacturer's view involves three distinct features; the transformer, the switching apparatus, and the protective apparatus. To these items there should be added another and most important factor which is involved; that is, the saving in cost of the plant in locating the apparatus outdoors instead of indoors. As concerns the high-tension bus-bars, there is no good reason why these should not be located outside in every case, as they are practically a termination of the transmission line.

The apparatus directly involved in an outdoor installation comprises lightning-arrester equipment, choke-coils, oil switches, and transformers. With the adoption of the aluminum-cell lightning-arrester, which is built to-day for outdoor installations, there remain three factors for the designer to deal with. At the present time there are in outdoor operation numerous transformers wound for 10,000 volts; and there should be no reason why outdoor operation would not be possible with higher voltage. As for the oil switches, these can be made water-proof as readily as transformers.

In transmissions of 10,000 volts, where self-cooled transformers can be applied with the downward projecting insulated lead which issues from an overhanging pocket near the top of the transformer case, an outdoor application is perfectly safe where the transformer is located on an elevated platform; but for higher voltages, where the oil-insulated, water-cooled type of transformer is necessary, with the leads projecting out of the top of the case, several factors are to be considered. Owing to the weight, this transformer would necessarily have to be located on a foundation. In climates where severe snowstorms are encountered, the transformers and oil switches should be protected by some kind of shed, otherwise they are likely to become submerged, grounding the system. This shed is also a necessity in the summer months, to protect the oil-insulated apparatus from the intense heat of the sun's rays, as well as acting as a shield to the insulators of the apparatus from brick-throwers and sharpshooters. In addition to the shed covering the apparatus, the latter should also be surrounded by a wall or fence, in order to keep the inquisitive out of the danger zone.

In high-voltage transmissions the transformers should be protected on the high-tension side by disconnecting and automatic oil switches. On this point I cannot agree with the suggestion:

> * * * that by treating the high-tension side of the transformers as a part of the line, no high-tension oil switches would be required, but fused disconnecting switches placed on the high-tension side would serve to cut out the transformer.

This might apply on a 6600-volt line, but even in this case I would recommend oil switches. The fuse proposition on a 6600-volt line is a very expensive one, as good protective fuses are costly, especially owing to the number likely to blow. At the present stage of the art, in speaking of high-tension apparatus, we have in mind voltages from 40,000 up; fuses for such voltages would be absolutely prohibitive as well as poor practice.

In describing an outside station, Mr. Randall says that as no instruments are employed, no attendants are necessary. I do not agree with this statement unless the station is located in close proximity to another station containing the low-tension apparatus, so that the switching can be readily looked after, or the switches are electrically operated from a distance. If a station were connected on the high-tension side by only fused disconnecting switches, any possible trouble that might occur—blowing a fuse—would cause an inconvenience that might not only be annoying but costly to the consumer.

If it is desirable to locate the high-tension apparatus outside, the ideal arrangement for a switching or transformer station where no secondary machinery—as motor-generators—is necessary, would be to locate the apparatus—including the lightning arresters, choke-coils, oil switches and transformers—under a shed, the station being surrounded by a fence in populated districts, the low-tension apparatus, consisting of switchboard, etc., being housed. The transformers should be protected by electrically operated oil switches, operated from the switchboard by the station attendant, and by disconnecting switches on the high-tension side. If the low-tension voltage for distribution is 2300 volts, hand-operated automatic oil switches, mounted on the back of the switchboard, and disconnecting switches should be used between the secondary of the transformers and the low-tension bus-bar. If the low-tension voltage is 440 volts or thereabouts a saving could be made in the switching apparatus on the secondary by using only disconnecting switches between the transformer and the bus-bar, the outgoing feeders being protected by triple-pole, carbon-break circuit-breakers with overload release.

In using water-cooled transformers, it is essential in such a layout that attention be given to the cooling-water piping to prevent bursting from freezing, which necessitates the flow of water continuously through the coils. It is also necessary that the attendant know at all times that this water is flowing. This can be taken care of by inserting a quick-flow indicator in the main water line, which should run through the station, and one on the incoming water piping at each transformer. This device shows the operator at a glance whether or not the water is flowing, and can be seen 25 ft. distant. To my knowledge it is the only safe device on the market for such an indication. It is now made electrically operated so that when the water stops flowing a lamp will be lighted.

I had the pleasure of assisting Mr. Randall in the estimates of costs of indoor and outdoor stations. In making these calculations it was apparent that in stations containing secondary machinery, as motor-generator sets, or synchronous converters, the percentage of saving in placing the high-tension apparatus outdoors, instead of in compartments indoors, is very small, as there is involved only the cost of the building against the total cost of the installation plus the additional cost of weatherproofing the outside apparatus. It was evident that this percentage of saving decreases as the size of the station increases for a larger amount of secondary apparatus. In such cases the saving would not warrant locating the apparatus outdoors, due to the fact that with the transformers and switching apparatus in compartments they are absolutely protected from the weather, are more accessible for inspection or overhauling, and out of the way of molesters. The life hazard is less also. In simple transformer or switching stations, such as tapping from the transmission line to feed an outlying district for lighting and motor work, there is no doubt that by locating the high-tension apparatus outside, protected by a fence and shed covering, with the low-tension switch-board and switches housed, a saving in cost is effected well worth considering.

As regards locating oil switches outside of a station, under a lean-to, as suggested, I have at present in hand such a problem. The plant in question is now generating 36,000 kw. at 60,000 volts, delta. The output of the station is to be increased to 56,000 kw. by the addition of two vertical-type water-wheel-driven 10,000-kw. generators, and the transmission pressure raised to 85,000 volts, Y, with grounded neutral. The switches and bus-bars are now installed in masonry compartments, and it would be impossible, owing to conditions existing, to use a 100,000-volt tubular switch which was desired, erected in the station, without tearing out the present bus-bar structure, involving a large expense.

The problem reverted to whether the insulating qualities and rupturing capacity of the present switches could not be increased to take care of the new conditions. The manufacturers found after a careful study of the situation that the pots of these switches could be made 6 in. deeper and 2 in. larger in diameter, increasing the oil space approximately 50 per cent and doubling the expansion chamber or air space above the oil, thus greatly increasing the insulating and rupturing capacity of the switches. From tests it was found that the insulation was satisfactory, but as there were no facilities in the factory for testing the rupturing capacity, this is not known; but there is no question that the switches are perfectly safe for the high-tension side of any bank of transformers, the maximum normal capacity of the largest bank being 18,000 kw. It is deemed advisable to install an outdoor 100,000-volt switch with a rupturing capacity of 200,000-kw. and this proposition is now before the engineers of the manufacturing companies. There is no doubt in my mind that the design of such a switch is not only possible, but will be called for frequently in the future.

These outdoor switches will be used only on the outgoing lines from the power house and incoming lines to the sub-stations, operating at 85,000 volts, Y, with grounded neutral. I am quite sure that these switches can be built, as the manufacturers are anxious to submit prices to take care of such a proposition.

M. W. Franklin: Fig. 1 in Mr. Reynders' paper shows the potential curve in the dielectric between the surface of the conductor and the grounded external circumference of the dielectric. The statement to the effect that it shows the distribution of stress is an error. Stress, which in this case corresponds with intensity of electrification, is the space-rate of change of potential and is therefore represented by the graph, not of the potential, but of the first derivative of the potential with respect to space.

The equations for the potential at any point between two coaxial cylinders must satisfy the condition.

$$\Delta^2 V = 0 \qquad (1)$$

The equipotential surfaces are coaxial cylinders and therefore (1) may be written

$$\frac{d^2 V}{d r^2}+\frac{1}{r}\ \frac{d V}{d r}=0 \tag{2}$$

which on integration gives:

$$V = c \log r + C_1 \tag{3}$$

when $r = R_1$, $V = V_1$ and when $r = R_2$, $V = V_2$, therefore

$$V = V_1 \frac{\log \dfrac{R_2}{r}}{\log \dfrac{R_2}{R_1}} + V_2 \frac{\log \dfrac{r}{R_1}}{\log \dfrac{R_2}{R_1}} \tag{4}$$

where V_1 R_1 and V_2 R_2 are respectively the potentials and radii of the inner and outer cylinders, and r is the distance of any point at potential V from the common axis.

The intensity of electrification at any point R at a distance r from the axis is

$$\mathfrak{J} = -\frac{d V}{d r} = \frac{-(V_2 - V_1)}{r \log \dfrac{R_2}{R_1}} \tag{5}$$

This represents the force.

In the case of a homogenous, continuous dielectric, V_2 is at the outer circumference and is equal to zero. The equation (4) may then be written:

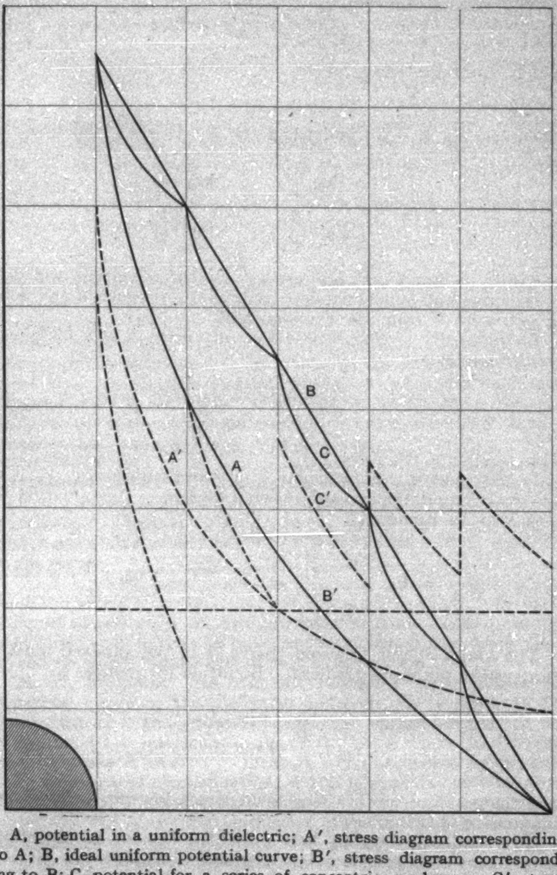
$$V = V_1 \frac{\log \dfrac{R_2}{r}}{\log \dfrac{R_2}{R_1}} = c \log \frac{C_1}{r} = k \log \ \frac{1}{r} \tag{6}$$

The graph of this function (curve A in the annexed illustration) is the potential gradient. Equation (5) reduces to:

$$\mathfrak{J} = \frac{V_1}{\log\left(\dfrac{R_2}{R_1}\right) r} = \frac{C_2}{rg}\ \frac{1}{r} \tag{7}$$

and the graph of this function is the stress diagram and is shown in curve A'.

The condenser bushing here presented has for its object the attainment of a uniform potential gradient, as shown in curve B. The reason for this is that the derivative of such a function is a constant, as graphed at B', which shows that the force at any point in the dielectric is constant.



A, potential in a uniform dielectric; A′, stress diagram corresponding to A; B, ideal uniform potential curve; B′, stress diagram corresponding to B; C, potential for a series of concentric condensers; C′, stress diagram corresponding to C.

To this end, the dielectric is divided into a series of concentric cylinders, each forming the dielectric of a condenser whose plates consist of sheets of tin-foil interposed between them. The difference in potential between each plate and the next succeeding is a constant quantity, so that a line through the positions of the plates would indicate a potential curve as at *B*.

Were the number of plates infinite this would be strictly true throughout the dielectric, but in the case shown the stress gradient in the individual layers of dielectric must exert upon the results an influence which is not negligible.

The equation (4) for potential shows that though the potential differences between pairs of adjacent plates be uniform, the potential in the contained dielectric is not a straight line, but a logarithmic curve determined by equation (4). This is shown in the curves *C*.

The stresses in each section of the dielectric are shown in the curves *C′* which are the first derivatives of the curves *C*.

Referring to equation (4), it will be seen that the shapes of the logarithmic curves *C* differ as the position of the shell changes with respect to the distance from the center. The differences could not be shown in the small diagram.

Reference to equation (5) shows that the potential difference $f(v)$ being a constant for all shells, the constant $\log \frac{R_2}{R_1}$ varies with varying distance from center. The ratio $\frac{R_2}{R_1}$ becomes smaller while the value r becomes greater.

$\text{Log} \frac{R_2}{R_1}$ is a discontinuous function, and does not therefore lend itself readily to pure analysis, but correctly formed stress diagrams are plotted for each of several values of the function. These curves show that the stress diagram, far from being a straight line or even a smooth curve, is a series of discontinuous curves which introduce serious stresses in the dielectric. They also show that the stress distribution is very irregular, being greatest near the conductor, as with a uniform dielectric.

Geometrical considerations as mentioned in the paper necessitate the employment of various dielectric media to obtain equal capacities. This is unfortunate, as the different layers will expand and contract unequally, and mechanical strains of a serious nature will probably result.

The impossibility of avoiding sharp ridges and prominences on the surface of the foil will result in localized high potentials which will probably cause puncture.

Coaxial cylinders when charged are in a state of unstable equilibrium. When they are displaced even a small amount the capacity rapidly rises, the rise being proportional to the square and higher powers of the displacement of the centers. In the imperfectly rolled cylinders the irregularities correspond to equivalent displacements of center, and the stresses across certain limited areas of dielectric will be greatly increased.

K. C. Randall: The joints which were described as "vacuum tight" were so called as a measure of good joints. Mr. Moody's suggestion to maintain a weak pressure, so that there would be a slight outward pressure in order that any leakage would be outward instead of inward, is one that has frequently been looked upon with favor. It is true that the oil may freeze and become temporarily less effective through losing its insulating qualities, but the usual insulation margin in the quality of oil is sufficient to care for such a condition. Oil that will withstand 50,000 volts may drop down to 10,000 or 15,000 volts, and yet this very considerable depreciation in the insulating qualities of the oil may occur and the oil still be serviceable. The ordinary substations are not carefully heated. Furthermore, the heat due to the loss in most transformers will prevent the oil freezing solid. It is obvious that should the water in the cooling pipes freeze, the pipes would split and the next time water was turned on the transformer would probably be ruined. The obvious remedy is to adopt some means to keep the water from freezing, or arrange to drain the pipes.

Mr. Thomas pointed out the troubles of inspection and investigation, and particularly the daily routine of looking after the apparatus. That is more difficult, it is true, but the underlying fact is that nowadays our apparatus is getting better and better. A few years ago an occasional failure, or even a frequent failure, was not very much thought of. To-day a good deal of trouble is raised at a single suggestion of failure. How many moderately large transformers are taken apart and cleaned, or even looked over thoroughly? Once a year probably some of them are examined, but a goodly share are not. It would be difficult to repair an outdoor unit in a snowstorm, no doubt. The reference made to the heliostat seems to have been taken seriously by some one.

To summarize what I have said in the paper. Outdoor apparatus is not a panacea. There are places where it can be and will be used: there are some places where it is used to-day.

Mr. Mershon asked at what temperature cold oil would stop switches from operating. I cannot say positively, but I believe there is a non-freezing oil which at a temperature 35° fahr. below zero will still permit switches to operate.

In an outdoor installation the isolation of the units will be cheaper than for indoor stations, and consequently the security resulting from wide separation of units is more cheaply obtained.

Tight joints for transformer cases are equally desirable for indoor and outdoor units, so far as "breathing" is concerned, but the outdoor units require protection against rain, storm, dust, etc., not needed by indoor apparatus.

The standard 150-mil gap will give a test of from 6000 to 10,000 volts in oil taken from a tank with water under the oil. There are, doubtless, many transformers for 10,000 volts and over which are operating with water standing in the bottom of the case. It is also likely that an average test value of many oil samples taken from transformers in moderately high-tension service would not exceed 20,000 volts. The writer recalls a 60,000-volt unit which continues in perfect service, though the oil at one time tested only 15,000 volts.

These are some of the reasons for feeling that the limited depreciation of the oil dielectric due to freezing—which is quite improbable—will not endanger modern large outdoor transformers.

The field of the outdoor transformers is limited, but there are some notably economical installations. The Ontario Power Company is reported to have saved $2000 by an installation of 60,000-volt outdoor series transformers alone.

There are a few large outdoor 6600-volt transformer installations which are just as simple and satisfactory as the small house-to-house transformer installation.

Except in the very remote case of failure, it will not be necessary to inspect or work around outdoor apparatus, save in favorable weather chosen for the purpose.

A. B. Reynders: In Mr. Moody's remarks the lining up of the weak spots in the insulation was mentioned, and several subsequent speakers have brought out the same point. It is true that the weak spots tend to line up, especially if the insulation be thin. We have made terminals with three layers of 0.005 in. paper between tin-foil layers, and the terminal on test broke down at a relatively low value. The thickness now employed in the design practically eliminates this weakness. Mr. Moody also stated that the design employing oil, separated into layers by barriers of insulating materials, gave a very high dielectric strength. This is true, as the barriers of insulation act as an interference to the lining up of the particles of oil when under stress. This arrangement is not in any sense a condenser terminal.

The length of the condenser terminal above the top of the tank has been criticized as excessive. I wish to say that these terminals were purposely designed long. Observe the 66,000-volt terminal. This is used on an oil circuit-breaker. The operating mechanism is placed between the poles. As this mechanism extends some distance above the cover, and as it is necessary to obtain somewhat more than sparking distance between the top of this mechanism and the tip of the terminals, it required long terminals. Compare the terminal having a test of 180,000 volts with the terminal having a test of 250,000 volts. The latter is used on a transformer. It will be noted that the surface insulation distance in air is about the same as on the 66,000-volt circuit-breaker terminal. It will be further noted that the outside grounded band is extremely long. This is required by the design of the transformer tank and cover. It is necessary to have the lower end of the outside grounded band under oil and also to have the upper end of the same band on a level with or a little above the top of the cover. Owing to the "dome" required by the cover to withstand pressure, this long distance is necessary. Observe the short distance required under oil—in this terminal having 250,000-volts test, it is only 12.5 in., making 20,000 volts per inch.

Mr. Thomas spoke in favor of terminals of large diameter. This meets with no objection in the design of transformers, but for circuit-breakers it is practically impossible. For instance, a 100,000-volt circuit-breaker would require a terminal of the "bulk" type 20 in. in diameter, while the tank required would not permit the use of such large terminals.

Mr. Rushmore stated that brush discharge is detrimental, that it is doubtful if the condenser terminal will stand the test of time. We have made these terminals for 2 years and some of them are operating to-day at 200,000 volts to ground.

Mr. Neall thinks that manufacturing limits are reached in the terminals shown in this exhibit. I can state that we are now building a terminal for a test of 400,000 volts for 1 min., having approximately a diameter of 10 in. and a length of 117 in. We have a design under way for a terminal for a 500,000-volt transformer—one end grounded—having approximately a diameter between 15 in. and 20 in. and a length of 15 ft.

Mr. de Muralt stated that the factor of safety in terminals is too small for ordinary conditions of working. At the present time we are designing terminals for a test voltage which in commercial service is 2.5 times the normal operating voltage. The stress chosen for this test voltage is never more than one-half of the breakdown value of the insulating material, hence the terminals have at least a factor of safety of five.

Two of the speakers touched upon the theory of this terminal and attempted to show that either the addition of tin-foil did not improve the puncture value or else it was liable to produce harm in time. I will not take the time to answer these arguments, but wish to refer them to Jona's paper previously mentioned and particularly to a paper by Rudolph Nagel, published in the *Elektrische Bahnen U. Betriebe* for May 23, 1906.

Ralph W. Pope: I have here an insulator presented to the Institute by one of our charter members, E. P. Roberts of Cleveland. The inscription on the insulator is as follows:

> Insulator taken from old telegraph pole in Northern Wyoming about 1887 or 1888, by Wilbur C. Knight, mining engineer, and presented to E. P. Roberts, member of the A. I. E. E. The telegraph line was the first transcontinental and was built by Ezra Cornell, founder of Cornell University.

This type of insulator is peculiar. The early insulators were simply of glass; this insulator is of glass inside, and covered with a wooden shield. The object of the wooden shield is interesting. It was found that the glass insulators formed an excellent target for the marksmen of the plains, and the shattering of the glass was a never-ending source of amusement when the marksmen hit the insulator. Hence, this form of wooden shield was devised, so that the glass would not shatter. Consequently this type of insulator was generally used all through the plains. It was commonly known as the "nigger head" insulator.

F. G. Baum (by letter): In the early work of the transmission companies on the Pacific coast problems had to be solved within certain prescribed expenditures. What we were trying to obtain was a satisfactory delivery of power to small consumers without great expense or danger to persons or property. In some cases the transformers were set outdoors on ties and a shed built over them to keep out moisture, all switches, fuses, etc., being also outdoors. Many of the stations had no operators and often were visited only monthly, and the simpler the layout the better.

FIG. 1.—Interior of sub-station, showing early type of switches.

Fig. 1 shows one of the earliest interior sub-stations, with single-pole switches mounted on a wood frame, making the fire hazard very great. It was this sort of thing that kept the men on the alert day and night. Now nearly all the air-break switches and fuses are installed outdoors. Fig. 2 shows a modern type of switch. Fig. 3, 4, and 5 show some of the earlier types which may be interesting from a historical point of view.

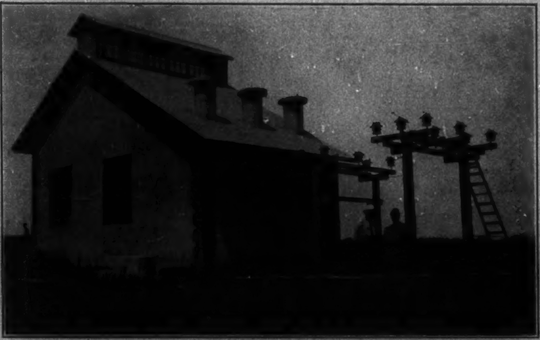


FIG. 2.—Modern outdoor switch with fuse.

As voltages increase and power consumption becomes more general, there will arise a demand for transformer apparatus and switches to be mounted outdoors, thus at once reducing the investment, facilitating inspection, reducing fire risks, and decreasing operation costs.

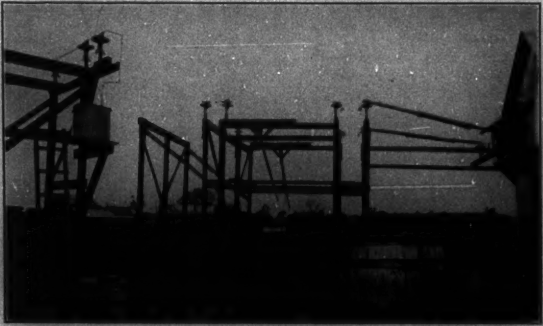


FIG. 3.—Early outdoor switches. Compare the choke-coil lightning arresters with Fig. 10 of Mr. Randall's paper.

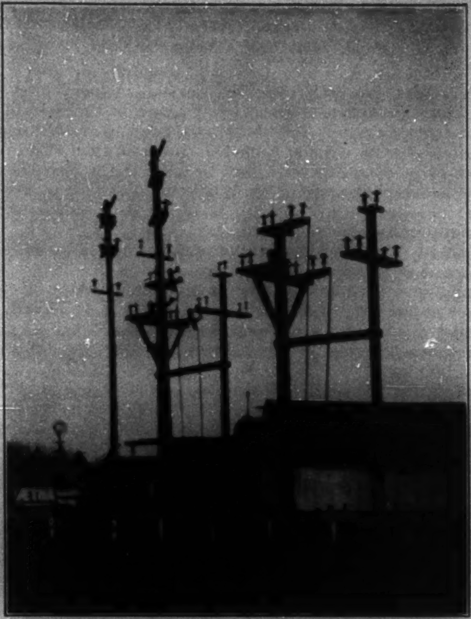


FIG. 4.—Early outdoor switches.

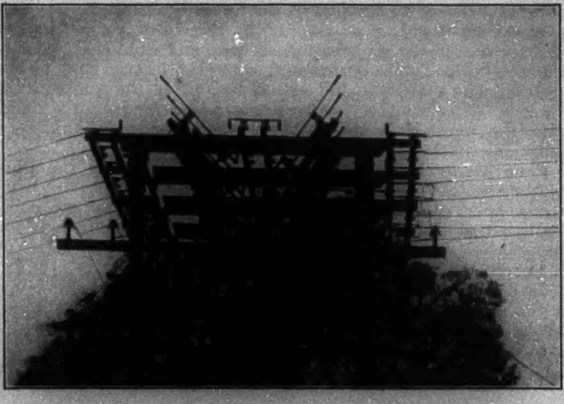


FIG. 5.—Early outdoor switches.

O. S. Lyford, Jr. (by letter): Mr. Randall's paper relates to one of the most important steps recently taken in the field of high-tension transmission. The indoor sub-station, with apparatus operated at 40,000 volts or higher, is an absurdity. Not only is the cost of housing excessive, but because of the obvious necessity of economizing space as much as possible an excessive amount of engineering expense is incurred in developing the most compact safe arrangement.

The merit of the outdoor station will be most apparent where the amount of power to be transformed is small. Transmission companies are continually facing the problem of taking off blocks of power of 500-kw., or less at isolated points. At 40,000 volts, or higher, the cost of a sub-station, with the usual controlling and protecting devices suitably housed, is not very different for 100 or 1,000-kw.

The cost for the small sub-station, even of the outdoor type, will always be disproportionately high, but much can be done toward minimizing the cost by concentrating the transformer, circuit-breaker, and choke-coil in one tank. This plan was proposed at the Niagara Falls convention in 1907 and is referred to in Mr. Randall's paper. The merit in saving terminals is apparent from an inspection of Figs. 4 and 6.

Mr. Randall also refers to the recent development of a transformer construction which permits of shipment in the case with the necessary oil. If we can have a self-contained sub-station unit, ready for setting up in the field, and requiring with it only a small shelter for low-tension switching equipment and for repair purposes, the problem will be greatly simplified and the cost brought within reason.

Referring to the difficulty with moisture, the extent of breathing of a transformer is hard to realize without actual experience. The variation of oil level with change of temperature is much greater than would be represented by the respective coefficients of expansion of the oil, transformer core, and windings. This is apparently due to the porous and somewhat loosely built up insulation which absorbs and expels the oil as the temperature changes. This tendency to breathe can be provided for without admitting moist air to the interior of the transformer tank, if an adaptation of the U tube, with an oil seal, be used.

Referring to the terminals for outdoor transformers, the illustrations indicate that porcelain and composition types are both being experimented with. The writer has yet to see any composition material that has proved adequate for use in outdoor high-tension work. The vitreous quality and high glaze of porcelain seem to be essential.

Carl Schwartz (by letter): Two advantages are claimed in favor of the outdoor station: first, the cheapening of the installation due to a saving in building; and secondly, less life and property hazard.

Which type of installation, outdoor or indoor, is the most economical is not determined by low first cost alone. Any difference between the two schemes in cost of operation and maintenance should be capitalized and balanced against a difference in first cost. Also the value of safety of operation will have to be most carefully considered, even if this feature cannot be estimated in dollars and cents.

Reliability of service in generation and distribution of electric power has become of greater importance from year to year, and is recognized to be in almost all cases the most important feature. It will be admitted that delicate apparatus with complicated connections is apt to operate more reliably, can be better cared for and maintained for less money, if installed in suitably constructed buildings instead of outdoors. Inspection of oil switches placed outdoors is frequently difficult; dust, rain, and snow may cause serious disturbances at any time, if not during inspection.

Mr. Randall says:

> In order to obtain the cost comparison, the cost of the station grounds and indoor apparatus must be balanced, not only against the smaller building, but also against all the ground required for the outdoor apparatus, the outdoor apparatus itself, and the instruments and the indoor control apparatus.

In the estimate, however, the larger area occupied by the outdoor arrangement is not considered, and the saving in first cost shown in favor of the latter is to be reduced accordingly.

The two estimates for an indoor and semi-outdoor motor-generator sub-station show a saving of about $13,000 in favor of the outdoor scheme. This saving will be reduced to about $4,000 if the size of building is made more proportionate to the apparatus to be accomodated, and if the same class of building be assumed for both cases. Also, the same class of building will probably be erected whether some of the apparatus is installed indoors or outdoors, the general requirements being entirely similar. There is hardly reason for constructing a building of a cheaper class if only the smallest part of the apparatus be taken outdoors.

Hence it appears that the outdoor type of station may be somewhat more economical in case of a very simple transformer or switching station of high voltage with few or no instruments.

For a motor-generator station or a station requiring numerous instruments and attendance, the first cost of an outdoor station is not appreciably, if any, lower than of an indoor station, greater economy in operation and maintenance and greater reliability always being in favor of the latter.

As far as less life hazard is concerned, the outdoor station is distinctly more dangerous unless it is protected against intruders in a most thorough manner. The property hazard, if this is meant to apply to the station building proper, even taking into account large quantities of oil stored in switches or transformers, is, as experience shows, extremely small if the station is sufficiently sectionalized and otherwise well designed, and is far overbalanced by the better protection afforded to the apparatus.

Concluding, I wish to say that we are fortunate in having available apparently well designed apparatus such as that described in the paper for use outdoors even under adverse climatic conditions. We know of circumstances where apparatus of such type can be used to advantage. I believe, however, that it would not be wise to promote the building of outdoor stations and to develop apparatus for them, to save in first cost by sacrificing reliability, while increasing costs of operation and maintenance. It would rather appear advisable to endeavor to limit the use of outdoor-type transformers, switches, etc., to cases where complicated connections and other undesirable features result, should such apparatus not be located close to the line and should it become necessary to bring high-potential wires with perhaps numerous crossings to and into buildings. This applies, for instance, to sectionalizing switches of high-voltage trolley line systems where the location of such switches away from the line would cause serious complication, though in this case the use of high-tension switches of the outdoor type is to be considered as one of the disadvantages of the system.

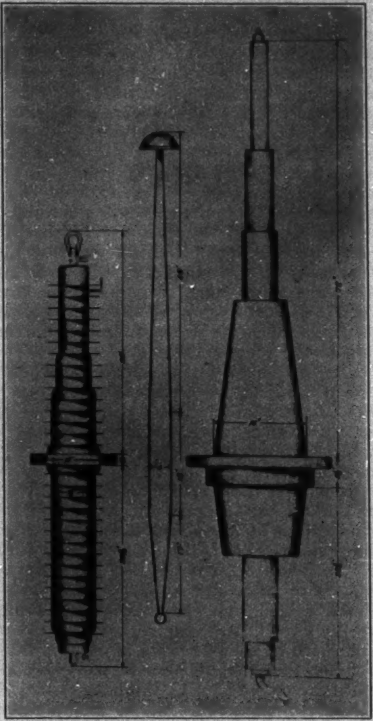
J. B. Whitehead (by letter): The most general expression for the capacity of two concentric cylinders is

$$C = \frac{k\,l + \Delta\,l}{2 \log \frac{r_2}{r_1}}$$

Δl is the correction term which depends on the length of the cylinders, their diameters, and the shape of the ends. The exact value of Δl leads to complicated expressions if it is attempted to express it for all cases. It is not probable that the requirements of terminals such as are here treated would necessitate taking account of this corrective value. The value of Δl for two cylinders 60 cm. in length and of radii 12.5 and 14.5 cm., respectively, with square ends, is between 2 and 3 per cent. Consequently, for the long narrow tubes as used in the terminals, even the difference of length of successive tubes would probably not introduce any error which could not be allowed for under the conditions of construction. It is well to note, however, the suggestion of this type of insulation for use in transformers between primary and secondary and primary and ground. In such cases the dimensions would frequently lead to short cylinders of large diameters. If the exposed surfaces of the ends go to large values in order to prevent creepage, it is not impossible that it will be necessary to take account of the end correction in the simple expression for the capacity concentric cylinders.

Referring to Mr. Randall's paper, a preventive for the trouble arising from the breathing of moist air in transformers might be found in the use of a double valve in which the ingoing air is carried through a drying agent and a free-one-way outlet is provided for expansion. In this way no pressure due to increased temperature would be applied to gaskets and other joints which it is aimed to make absolutely air-tight. It would be interesting to know also whether any investigation has been made as to the value of drying agents located in bulk within the transformer case.

John J. Frank (by letter): Supplementing the remarks by Mr. Moody relative to the oil-filled lead which we have developed, I would like to call attention to the illustration herewith showing a comparison of dimensions of such a lead with similar leads shown in Figs. 10 and 11. This lead has actually been tested and shows a failure by arc from terminal to ground of 250,000 volts. Attention is called to the reduced height of the lead as compared with the condenser type, Fig. 11, and the solid type as



shown in Fig. 10, which reduction in height was referred to by Mr. Moody as a desirable feature in the design of any lead.

W. L. Waters (by letter): The grading of insulation in high-voltage cables was first suggested by O'Gorman about 10 years ago, as a means of reducing the excessive amount of insulating material required in a high-tension cable with homogeneous dielectric. It was found, however, that the variation in the specific inductive capacity and dielectric strength of available insulating material was too small to obtain any very great commercial advantage from this arrangement. The condenser-type of terminal was next suggested about 4 years ago as a means of obtaining uniform stress on a homogeneous dielectric. As Mr. Reynders has pointed out, this type is limited by the necessity of obtaining sufficient leakage distance between the various metallic cylinders on the outer surface of the terminal. The terminal which Mr. Reynders has developed by combining the above two principles is the first really practical commercial type of high-tension terminal.

When the condenser type of insulation was first proposed, it was suggested that it might also prove advantageous for use in alternators and transformers. Its use for slot insulation on high-tension alternators was suggested as a means of avoiding the brush discharge from sharp corners on the laminations of conductors, and of avoiding the weakening effect of the air spaces usually present in a dielectric of considerable thickness built up in layers. Up to the present, however, it has been considered that in this case the difficulty of making a satisfactory mechanical construction more than counterbalances any possible advantage which might result. The advantages of this type of insulation for transformer work, as Mr. Reynders has pointed out, are very doubtful except in special cases.

It has long been recognized that the terminals were a weak point in a high-tension transformer, and that the solid type of terminal with uniform dielectric was of poor design on account of its high cost and great bulk, and on account of the difficulty of obtaining the dielectric perfectly homogeneous and free from defects. Mr. Reynders apparently decided that it was not worth while attempting to improve the solid type of terminal further, and took up the condenser type as being more promising.

L. L. Perry (by letter): Any engineer who has calculated the cost of a building to house switching apparatus for four or five high-tension circuits and a simple bus-bar, will appreciate the work done along the lines covered by Mr. Randall's paper. In planning several important transmissions, we have estimated on intermediate switching stations for the purpose of cross-connecting the good half of a defective circuit with the good half of a second defective circuit; and we have always concluded that it was not wise to spend the money until actual operation had demonstrated that the cost was warranted, especially since, at the beginning, the load is light and more spare circuits are available. It appears to me that for switching stations there is bound to be considerable development in the field treated of in this paper.

When we postponed the building of switching stations we hoped that the ground wire and the horn arrester would give more ample protection from lightning than the facts now show. Notwithstanding the great progress made in the last few years in arresters, it appears to-day that the greatest enemy to long-distance transmission is lightning. Our own experience has been confirmed by that of other engineers. A reasonable degree of protection has been obtained for the stations, but we still have before us the problem of the protection of the line insulators miles away from the stations. The overhead ground wire, the horn arrester, and the electrolytic arrester do not, so far as our experience goes, afford full protection. Since it seems improbable that full protection will be ever obtained, there are good reasons for putting in, on important transmissions, a certain number of switching stations, depending on the value of reliability. Such devices as have been used in the past have been crude, and there now seems to be a demand for more elaborate apparatus. Probably we shall soon use outdoor oil-switches on many of our lines of highest pressure, and their use on lines of lower pressure will increase.

Most transmission engineers have been confronted with the problem of tapping an important transmission for the supply of a few horse power; as a rule not only is there no money in it for the power company, but such tapping is a menace to the main transmission. If inexpensive devices are available it will be commercially possible to do things that the high cost of the older types of station prohibited.

But it would seem to many of us that high-tension outdoor transformers could have but a very limited application, for where reliability of service is of much value it will be found cheaper to house the transformers. As electricity is more and more applied to electrochemical and electrometallurgical work, where often low power cost is of paramount importance, the minimum investment will rule and will tend to develop the outdoor station.

Nevertheless it would not be surprising if the application of such outdoor apparatus extended to transmissions for which its advocates do not now urge its use. We have had occasion to build some 6000-volt street-transformer vaults for feeding general light and power mains. Some of these have been built to stand flooding, and in them water-proof switches, transformers, and fuses have been employed. We have built others where there is no danger of flooding and the ordinary type of switch and fuse apparatus has been used. Contrary to our expectation the water-proof type seems preferable for many good reasons. It will require long experience to determine which is more reliable in service. The compactness, safety, and ease of repair of the water-proof type are great advantages. These vaults are not, of course, comparable to high-tension stations, for we used lead-covered cable for bus-bars and leads; but they have been cited to show that sometimes quite unexpected results may be obtained where such radical methods are adopted.

It is to be noted that the author does not go into the question of reliability. Most engineers would probably assert that an outdoor station such as that described by Mr. Randall could be of advantage only where a very low price is charged for power.

Assuming 20 per cent on the investment to cover all annual costs such as interest, operation, maintenance, repairs, depreciation and profit, the yearly cost will be:

Indoor station, 20 per cent of $15,100 or	$3020.
Outdoor station, 20 per cent of $11,445 or	2289.
Yearly saving	$ 731.

The yearly saving on the basis of 2000 kw. is only $0.37 per kilowatt capacity. If power be sold for as low as $16.00 per kilowatt-year, 37 cents seems no large sum to pay for extra reliability. But if power be sold for $32.00 or $64.00 per kilowatt-year, the 37 cents seem inconsiderable. These assumptions were that in each case 20 per cent covers all annual charges; but it would seem that the repairs, maintenance, and depreciation on the outdoor station must be relatively higher.

J. N. Kelman (by letter): The switch shown in the accompanying illustrations was designed for outdoor service on 30,000-volt systems. It consists of a weather-proof, three-pole, oil switch and two sets of disconnecting switches installed on a galvanized-steel tower. The oil switch proper consists of three separate iron tanks, each containing mechanism that gives a double horizontal break per pole, this break being so located as to leave two-thirds of the total volume of oil above it. Over each tank is placed a two-part insulating cover which serves to hold the leads in place. The leads are wrapped with varnished cambric for their entire length and brought out of the tanks and down to the disconnecting switches through heavy porcelain tubes, into which they are sealed with a special compound, then passing through the covers of the tanks and the plates in the eaves, both of these being of a high-voltage insulating material mechanically strong and moisture proof. The leads are well extended below the eaves to give ample creepage distance to ground under any weather conditions, the porcelain tubes serving to protect the cambric from the weather, porcelain being used for this purpose as the best and most reliable material known at this time. The lower ends of the leads in the tanks are sealed into the tubes with an oil-proof cement which prevents the cambric insulation from "wicking" out the oil.

The switch is made weather-proof by closing the spaces between the tanks on the sides and the bottom with heavy galvanized iron securely held in place by bolts, and by placing over the top a two-part roof of the same material sufficiently large to give ample clearance. For convenience of inspection the roof sections are hinged at the ridge pole, and either side may be raised as desired after loosening a few thumb screws. The weather-proofing was given most careful thought, and it is claimed to be

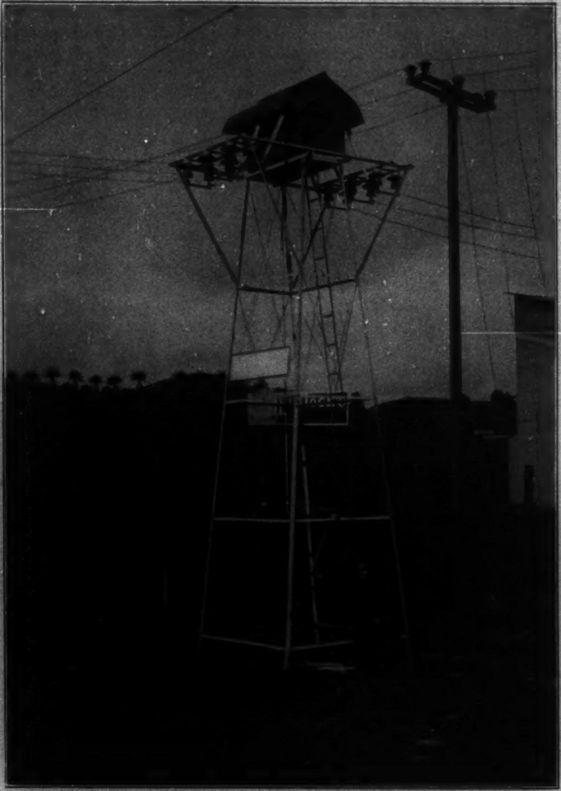


FIG. 1.—Outdoor switch and tower for 30,000 volt system.

impossible for rain or snow to enter the switch housing, either when falling quietly or when driven by high wind. The housing is designed to permit of circulation of air, thus keeping the temperature of the air within it about the same as that of the atmosphere. It is expected that the oil will absorb more or less moisture from the atmosphere. The insulation is designed to have a high factor of safety even with oil of very low insulating value.

As an insulation test this switch was erected and connected to a 50,000-volt line as follows: while the switch was being erected rain commenced falling, but as it was desired to get as complete a test as possible the work was continued in the rain; the tanks were filled with oil and the switch was connected to the line ready for the test. The pressure was then raised to 60,000 volts and held at that point for 10 min., a separate generator being used for this purpose. The line was then cut back into regular service at 50,000 volts, which was maintained on the switch continuously for 20 days. Rain was falling steadily during the installation and continued to fall steadily while the 60,000-volt test was being made and for over 24 hours thereafter. Following this rain and during the 20-day test there were a number of showers accompanied by high winds, and one storm which lasted over 12 hours During all these rains 50,000 volts was maintained on this 30,000-volt switch, with a generating capacity of over 25,000 kw. to hold up the voltage; but notwithstanding the fact that this was nearly double the voltage for which the switch was designed

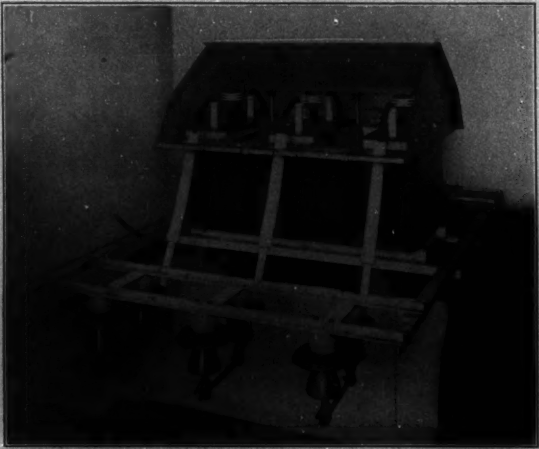


FIG. 2.—Weather-proof oil switch, leads encased in porcelain tubes.

there was absolutely no indication of distress or weakness at any point. The switch was tested on the lines of the Kern River Co., at Los Angeles, Cal.

August H Kruesi (by letter): The desirability of placing high-tension bus-bars, wiring, disconnecting switches, horn gaps for arresters, etc., out of doors is forcibly called to the attention of the designer in dealing with voltages above 33,000 on account of the very large clearances required for the higher potentials. A year and a half ago this led to a design in which practically all high-tension wiring is placed on the roof of sub-station buildings, as in Fig. 1, herewith, showing the development of special

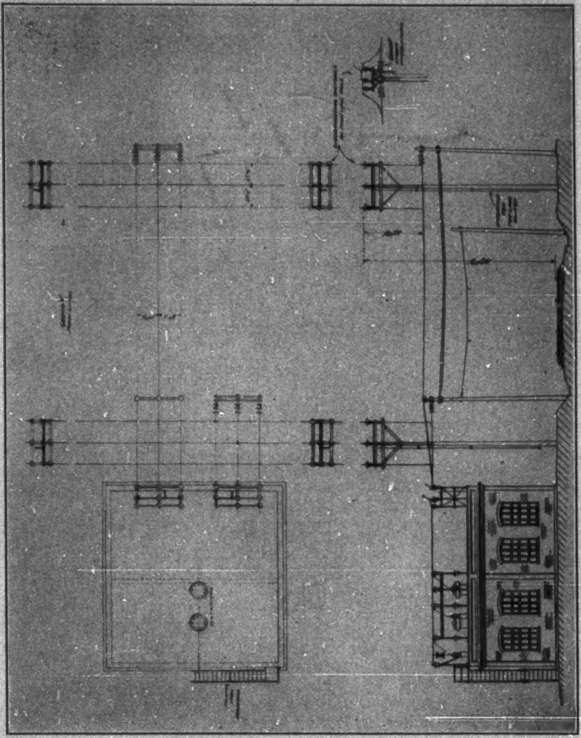


Fig. 1.—General arrangement of 60,000-volt converter sub-station and lines.

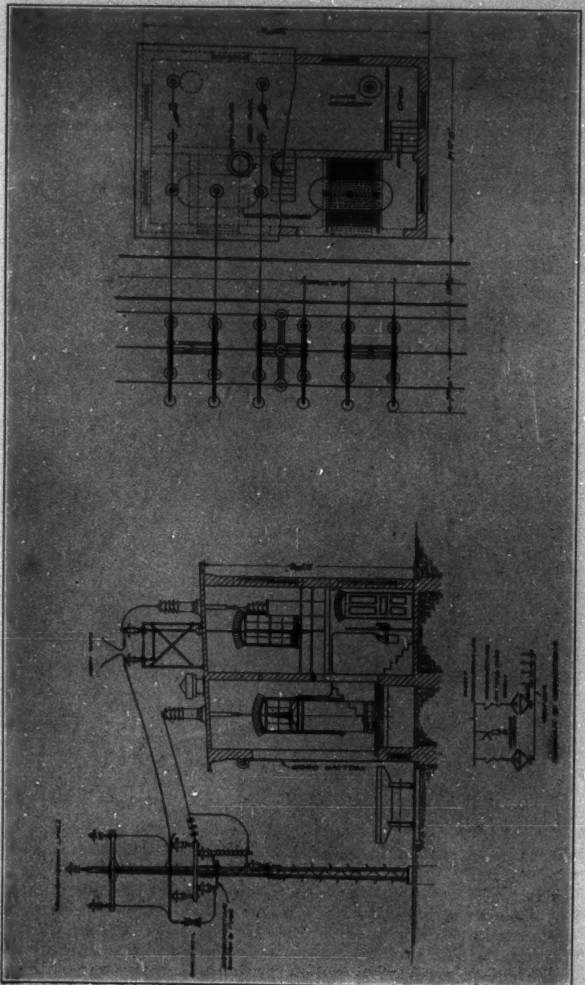


FIG. 2.—General arrangement of 200-kw., 60,000-volt transformer sub-station.

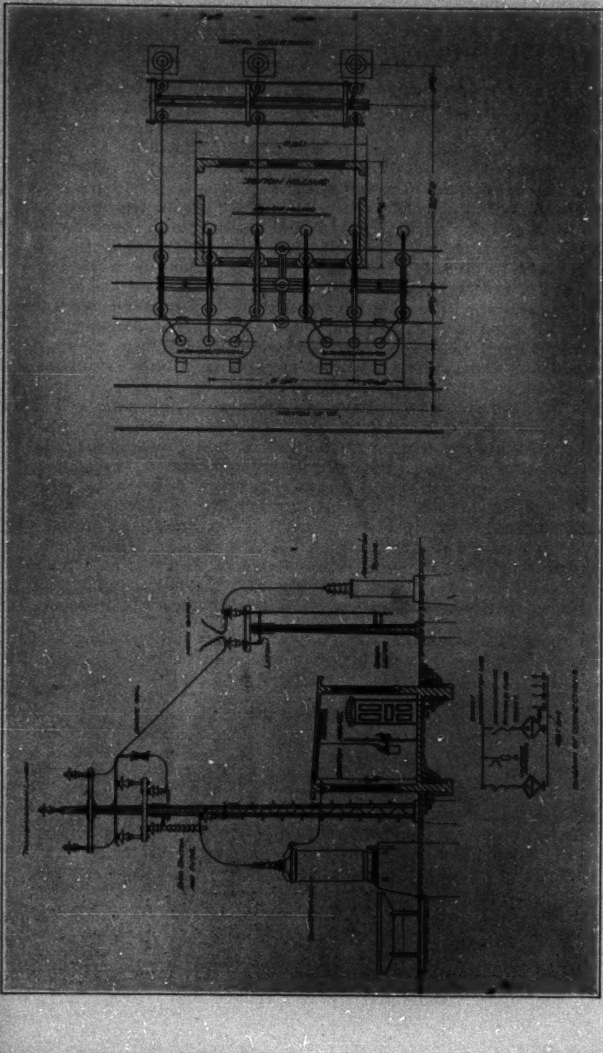


FIG. 3.—General arrangement of 200-kw., 60,000-volt transformer sub-station.

weather-proof disconnecting switches for operation from the floor, roof-entrance bushings, etc. Wherever a building is used for the apparatus this roof construction may be considered superior to mounting horn gaps, bus-bars, etc., on a number of poles. Ground space is economized, appearance is improved by reducing the number of poles, and the object of the poles; namely, to raise the high-tension wiring and switches to a safe height, is accomplished while the apparatus is not rendered so inaccessible as when mounted on poles. In fact it is more accessible than if placed inside in the upper part of a much higher building. The horn gaps and disconnecting switches may be operated from the inside of the building. The entire construction is suitable to all climates. Where converters, or other moving apparatus requiring attendance, is to be used, I consider this construction of the outdoor type to the extent indicated, very desirable.

The advantage of making the transformers weather-proof and placing all apparatus except the low-tension distributing switchboard outdoors becomes more apparent in the case of small high-tension transformer stations, which need only occasional attendance and may be protected by fuses on the high-tension side. The fuses require considerable clearance and may well be placed outside. In general, such stations will require some low-tension switchboard equipment, so that a small building will usually be necessary. A relatively large increase in the size of building is required to house the transformers. The use of fuses and the placing of recording watt-hour meters in the secondary circuit eliminate current and potential transformers and make a simple installation possible. Figs. 2 and 3 show comparative designs for a 200-kw. transformer sub-station. It is estimated that steel poles, a fire-proof brick building, and the best construction in all other respects, would show the following approximate costs:

Comparative estimates, 200-kw. transformer sub-station.
One transmission line, no high-tension oil switches.

	Indoor	Outdoor.
Two 100-kw., 60000/480-volt three-phase oil-cooled transformers	$ 5200	$ 5600
Switching equipment, insulators, one lightning-arrester Two 480-volt transformer panels Three 480-volt power feeder panels One 480-volt lightning feeder panel	3307	2847
Freight, installation, wiring of apparatus	1330	1250
Steel poles, cross-arms, and concrete bases	252	386
Building, piers for transformers, excavation, grading, etc.	2740	1022
	$12,829	$11,105

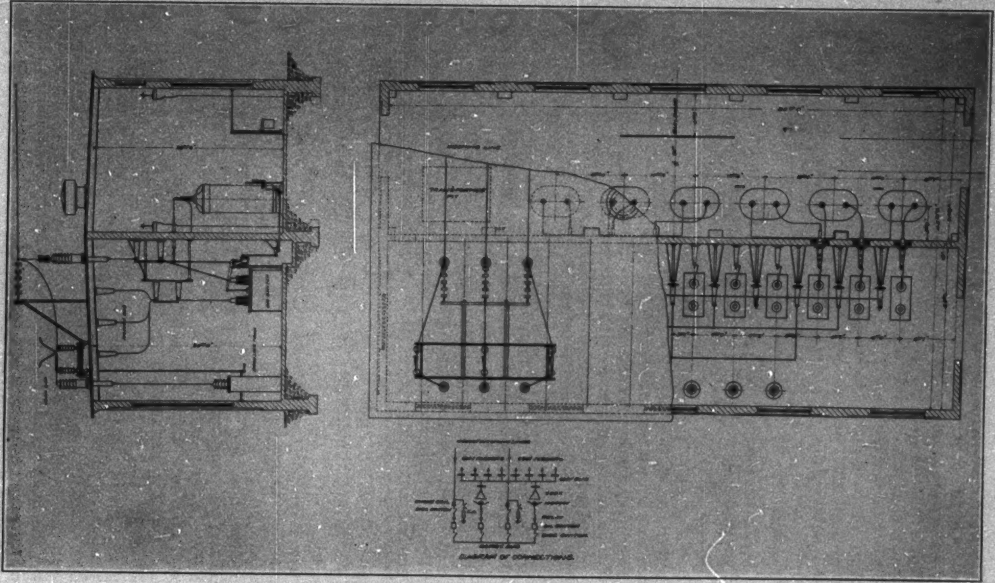


FIG. 4.—General arrangement of 2400-kw., 100,000-volt transformer sub-station.

The outoor construction shows a saving of $1724, or 15 per cent. On the other hand, the ground space required is about 20 per cent greater and the actual amount saved is so small as not to be a determining factor.

It would appear that the higher the line voltage to be dealt with the more advantageous outdoor construction should prove. By way of comparison, and to extend the comparison to much higher voltages than those covered in Mr. Randall's estimates, Figs. 4 and 5, showing designs of both types for a 2400-kw. sub-station at 100,000 volts, are added, together with the following approximate estimates:

Comparative estimates, 2400-kw. transformer sub-stations.
Two transmission lines with high-tension oil switches.

	Indoor	Outdoor
Six 400-kw. 100000/600-volt three-phase, oil-cooled transformers	$25,800	$27,750
Switching equipment, insulators,		
Two lightning-arresters, as per sketches		
Two incoming line panels with high-tension oil switches		
Two low-tension transformer panels complete		
Six power feeder panels complete		
Two lighting feeder panels complete	12,029	13,739
Freight, installation, wiring of apparatus	5700	5625
Steel poles and cross-arms, including concrete bases, steel framing on roof	104	433
Building, piers for transformers, excavating, grading, etc.	12,041	5870
TOTAL COST	$55,674	$53,417

The indoor estimate includes a 15-ton hand-operated crane and runways.

The small difference in cost—$2257, or 4 per cent—would not be decisive in any case, but the real difference in cost is masked in this design by the use of oil switches, not only for the transformers, but for the two transmission lines as well, and a building of considerable size in either case for these switches. The use of outdoor oil switches or fuses would make the building much smaller and eliminate 24 line entrance bushings. The outdoor type of installation is, therefore, dependent for a satisfactory showing on the placing of all high-tension apparatus outdoors. Merely locating the transformers outside does not accomplish very much in a large station, and, on the other hand, the oil switches may be considerably increased in cost and still show a substantial saving for the outdoor construction. Here again, as in the small station, the use of series relays for the oil switches, air-insulated choke-coils, and instruments on the low-tension side very materially simplify the arrangement.

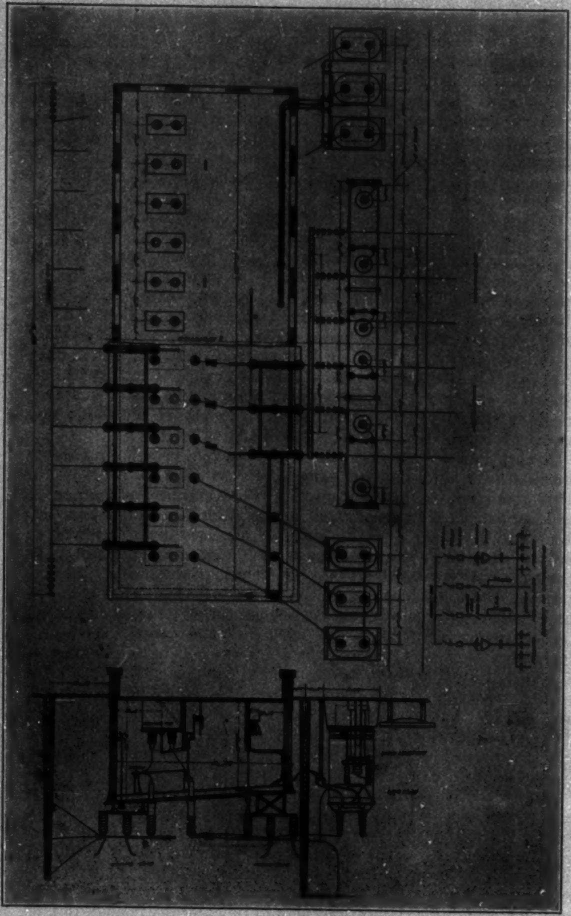


FIG. 5.—General arrangement of 2400-kw., 100,000-volt transformer sub-station.

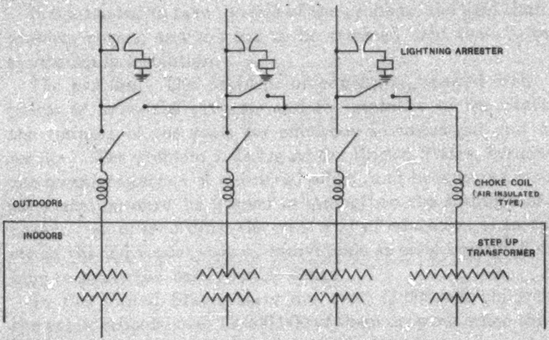
The necessity for making repairs on the spot may often determine the type of construction. A building covering all apparatus would generally be equipped with a crane, and the facility for repairing is a distinct advantage of the indoor construction. Exposing disconnecting switches to the weather will generally require a more expensive and complicated type of switch to avoid trouble from sleet and to insure safety to the operator. To work an ordinary knife-blade disconnecting switch indoors at 100,000 volts, a dry pole of about 16 ft. in length is considered necessary. To work a switch outdoors at the higher voltages in all kinds of weather, it seems imperative that a grounded metallic mechanism be used.

D. Kos (by letter): The interesting subject which has been treated in Mr. Randall's paper apparently thus far has been receiving attention only in America, as to my knowledge no outdoor high-tension switching equipments have been installed by European firms. Though at first sight the proposition looks very advantageous, there are a few points on which I would like to make some comments. When comparing the estimated costs for an indoor station and an outdoor station, it appears that only $200 is set aside for weather-proof coverings of oil switches, while it is estimated that the transformers can be made weatherproof for $1,000. or 6$\frac{3}{4}$ per cent more. It seems to me that these estimates, especially the first one, are somewhat low.

In addition, for outdoor service a heavier type of insulator must be used, and also an increase of cost must be allowed for series transformers and choke-coils. The outdoor structure is made of wood, which is rather a short-lived material at best. For reliability after a certain number of years from the time of construction, this certainly cannot be compared with inside construction work where no use has been made of wood as a building material. Here we have again the same comparison that was discussed rather often a few years ago when the advisability of using steel transmission towers or wooden poles was considered. Nowadays the general engineering opinion seems to be unanimous in favor of steel towers for very high voltages. The use of a wooden structure for an outdoor switching equipment for very high voltages cannot therefore be considered for a first-class job. These considerations largely alter the aspect, and when the outdoor station will be again estimated in accordance with the above the real difference of cost will probably be rather small.

But even if this difference of cost might amount to, say, more than 10 per cent, it remains to be considered, at least for the generating station, whether an indoor station should be chosen under any circumstances, as the advantage of repairing and overhauling during all conditions of weather outweighs a rather considerable extra expenditure. For sub-stations of small importance, however, Mr. Randall's suggestions should be carefully considered, as here the cost of switch gear per kilowatt is considerably higher than in the case of large sub-stations, so that the question of saving money versus decreasing facility of repairs assumes quite a different aspect in the two cases. For the generating station, the money saved per kilowatt is a minimum and the importance of reliability and facility of repairs is a maximum, so that at least here an outdoor station seems to be out of place.

It should be added, however, that though it be less desirable to install outdoors the transformers and other oil-filled apparatus, this objection does not hold good for bus-bars and plain disconnecting switches. For lightning-arresters it may even be an advantage. Outdoor stations, to the extent that they are used by Mr. Mershon in the Niagara, Lockport and Ontario Power Company, do not seem to have any disadvantages; but whether it is good engineering to go further along this line, as suggested by Mr. Randall, may reasonably be doubted, except for small sub-stations. For extremely high voltage the auxiliary apparatus, as oil switches, series transformers, oil-choke-coils, etc., become so cumbersome, voluminous, and costly and introduce so many new danger points in the system, that it is time to consider whether it is not better to do away with all of these as much as possible, and place all switches and instruments on the low-tension side only. For choke-coils ordinary air-insulated coils could be used outside and the end windings of the transformers should be reinforced an extra amount. The high-tension part of the switching equipment becomes therefore as shown herewith.



This switch shows three outgoing lines without oil-filled apparatus on the high-tension side and one spare transformer which can take the place of any of the other three. To simplify the sketch, the scheme has been shown with one line instead of three lines per feeder.

The arrangement is simple and without unnecessary vulnerable points on the high-tension side. Another set of lightning-arresters can be added on the transformer side of the choke-coils, if necessary. The only objection that can be raised is that there are no series transformers on the high-tension side, so that no separate protection of transformers can be applied according to the Merz and Price method. If desired, the transmission line as a whole, including step-up and step-down transformers, can be protected according to the Merz and Price system, provided that both sets of transformers are connected in the same way; for instance, Y on the high-tension and delta on the low-tension side.

A paper presented at a special meeting of the American Institute of Electrical Engineers New York, April 16, 1909.

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FUNDAMENTAL PRINCIPLES OF INDUSTRIAL EDUCATION*

BY HERMAN SCHNEIDER

It is intended to take the size of the problem, the field that the problem covers, and the end to be attained, and then to build synthetically a solution.

The problem. The problem of education, viewed from the points of industrial progress and the stability of the State, is the training of the mass for efficiency in industrial and civic service. The problem is as big as the United States, because of the interdependence of industrial effort, and because ultimately all education must be framed to strengthen the stability of the nation. In other words, the chief end of education is so to instruct the individual that all individuals as civic units will combine to make the best possible State.

In the United States there are over 18,000,000 children in the public schools; over 17,000,000 of them drop out when the law permits them to, and they go into agricultural, commercial, and industrial life. In the industrial centers they go into the factories and stores, but up to the time of leaving school they have not received one iota of industrial training that is worthy of the name. The size of the problem may perhaps be understood more clearly if it is stated in this way: if these 18,000,000 children were stretched across the country in a straight line, giving one linear foot of space to each child, the line would reach from the upper end of Maine to the lower end of California. That portion which goes through the high schools would reach across the state of California. The rest of the line from Maine to the eastern border of California is drawn into commercial, industrial, and agricultural life at about the age of 15 years, with no industrial training prior to going to work and practically no schooling thereafter. This proportion holds in any industrial town or city.

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*The aim of the Educational Committee is to lay before the Institute members the problems of industrial and technical education. Last year the committee devoted its attention to the problems of technical education. It has been deemed wise this year to present some phases of more elementary industrial training. To this end, Dean Schneider was invited to give the members of the Institute the results of his study and experience along this line. This he has done in a brief paper which is designed to provoke a discussion of the practical aspects of the training of men as mechanics, draftsmen, etc. A plan for applying the coöperative idea in electrical engineering education was outlined in a paper by Mr. M. W. Alexander, at the annual convention last year. Dean Schneider believes that the coöperative principle applies to industrial as well as to technical training and that it can be carried out in a practical manner.

Scope of the problem. The writer has heard many discussions on industrial education and has read many papers by very able writers. In almost every case the discussion has been contributed by the members of a society that represents a particular branch of industry, or the paper has been written by a man who feels that the trade with which he is most familiar is the most important of all. Members of the American Institute of Electrical Engineers, for instance, in discussing this problem, would usually not consider the educational situation from the point of view of the master tailor, the telephone company superintendent, the head of a department store, the pottery owner, or the building contractor. Investigation on this subject, covering a period of 9 years, discloses the curious fact that a man in almost any business considers the art of his trade as more difficult than the art of any other trade, and he inevitably insists that there must be trade schools to teach the children who go into his particular field of work. He is insisting at present that the public schools shall include specific training for his trade; and there is a general clamor from individuals and societies representing certain industries for the introduction of training in their particular trades into the public school system. Consider for a moment what this means.

If you take the industrial directory at the end of any city telephone book, and attempt to make a list of the trades therein shown, you will find, in a town like Cincinnati, that when you get to the letter E, you have almost one hundred distinct trades. The proposition of putting equipment into the public school system of Cincinnati to train the children for all the different trades in Cincinnati would make so top-heavy an organization, and necessitate so many buildings, that the imagination is staggered. Further, in many lines of industrial work the machinery becomes obsolete about every 7 years; if, then, the trades are to be properly taught in the schools, the equipment for the whole system must be changed at least once in 10 years. The advocates of trade instruction in the public school system evade these very essential facts by saying that the more important trades only should be taught. There are two phases to this latter proposition:

1. Who shall decide which are the more important trades? And how shall public support be obtained from all sources for these few trades?

2. Are the children to be taught a few trades, leaving all the other trades neglected, and leaving the predilections of the children out of question entirely? Or will only a few be trained in the more important trades, and the rest be allowed to shift for themselves as heretofore?

Should this be attempted, it would simply be a partial solution, and a very small one at that, of the whole problem of industrial education. If, for instance, we teach in the public schools the plumbing, machinist, wood-working, and moulding trades, what would be the solution for all the children entering the numerous other trades and commercial occupations?

There is, further, the taxpayer to take into consideration. Let us assume that you and I are residents of the same town, in moderate circumstances, and paying about the same amount of taxes. You have a boy and a girl and I have a boy and a girl. Your boy desires to be a machinist, and the public schools will take care of him; your girl desires to be a stenographer, and the public schools will probably take care of her. My boy wants to be a printer. Have I not the same right to demand that the public schools shall teach my son to be a printer, as you have that they teach your son to be a machinist? Shall the public school system say to my boy: you have got to be a machinist, plumber, moulder, or wood-worker, or go without a trade training? My girl wants to be a telephone exchange operator. Will you tell her that she has got to learn her work without any training? Is it fair for the owner of the machine shop to tell the telephone company that it must train its own help, when he demands that the public schools train his help?

In view of the foregoing, it should be obvious that any attempt to put trade schools; that is, schools that teach trades, into the public school system, would result in a tremendous expenditure of money for skilled teachers and for equipment which is not commercially productive. Any attempt to put in a few of the trades would afford only a slight solution of the question. The big problem would still be before us.

The situation. The size of the problem, and its scope, cause us to be confronted by a peculiar situation. In the first place the problem is so comprehensive that there is probably only one organized institution capable of carrying it; namely, the public school system. It ought not to need any argument to prove that private enterprise can not furnish the solution when an average city has 10,000 to 20,000 children to be educated every year, if they are to have industrial education. Figures are available, if they are necessary, to show the futility of private endeavor in industrial education. In the second place, to install a series of trade schools in the public schools is impossible, because of the expense and the inevitable complications.

Let us take account of stock. Every industrial center has a group of school buildings with its quotas of trained teachers. It also has many factories and commercial houses. Under present conditions most of the children who leave the public schools go at once into the industries or stores, and there is no connection whatever between school and shop. The children go to work not because they want to, but because they have to become little bread-winners. Here, then, are many children working in some capacity, and a series of public schools carried on only for those who are fortunate enough to be able to continue in their school work. Since the public school system is the only organized institution capable of dealing with all these children at work, and since the children are also learning a trade and earning money sufficient for their simple wants, it seems that the only complete solution of the problem is a system of coöperation between the schools and the factories for efficiency training and civic training of the young people after they have found their work.

How, then, can this coöperation be built up within the limits of reasonable economy? Fortunately, there are three or four experiments going on which indicate that a coöperative system is feasible in the trades, as it has been shown to be in engineering training. Several of these will be briefly described to indicate the various methods of solution.

The coöperative system. The fundamental principle of the coöperative system is very simple. It is this: the technique or the practical side of the work is taught only in a shop or store which is working under actual commercial conditions, and the science underlying the technique can be taught properly only by skilled teachers. All questions as to who shall supply the school teachers (the shop or the public); the hours the student works, and the hours he is taught; the periods of alternation of shop and school work, if alternating periods be used; and the curricula of the schools—all these are matters of detail to be considered for each particular case.

The economy of the system is at once apparent. In an engineering school, for instance, twice the number of students can be taught at about two-thirds the expense as compared with the four-year theoretical system. The same is probably true in industrial education, for under the coöperative plan the schools will not require any physical equipment; all their money can be used for brains and for buildings for teaching purposes only. There is a further economy to the student. In this case he is earning while he is learning, while under the trade school system he does not earn until he has completed his trade education. Parenthetically it should be stated that no displacement of the present high school courses is contemplated.

At Fitchburg, Mass., the coöperative system is a part of the public school system. The students are divided into two groups which alternate every week. That is to say, this week one-half of the students are in the day school and one-half are in the factories. Next Monday morning these groups will change, and those who are in the school this week will go to the shops, and those who are in the shops this week will go to the school. Since the public school becomes a part of the apprenticeship system, it has a voice in the organization of the apprentice course in the shop, and is *in loco parentis* to the boy, so far as his shop work is concerned. It ought to be obvious that the boy will receive a fair training in the shop because the school is in a measure watching over this phase of his work.

It is not intended, of course, that this plan should apply only to factories. It will apply to a boy learning the tailor trade, the butcher trade, the baker trade, or any other trade. It is necessary, however, to obtain two boys to alternate in the shops.

The course in Fitchburg is of 5 years' duration. At the end of that time the student has been taught the simple science underlying his trade; he has been taught shop mathematics; he has been given a certain amount of cultural work; he has become a fair mechanic. In brief, he is at the beginning of specialization.

It has been found further that the money earned every alternate week, and for full time during the summer, is sufficient to pay for the simple wants of these children. It is also true that there is seldom an instance when a child is hindered by financial conditions from taking such a course.

A number of changes in the system of administration have been found necessary, and these details will be considered to show certain phases of the working of the system. In the first place, the grade school principal is responsible to the school authorities for every boy in his district. When the boy leaves school at the legal age, the grade school principal is required to follow him and ascertain what he is doing. He then consults the parents of the boy and the boy's employer, and the question of the future of the boy is immediately shifted to them. The employer is urged to enter into a combination with the school in the effort to make the boy more efficient at his work, and to give him a little more general education than he would otherwise obtain. The fact is impressed upon the young man and his parents that he ought to make a choice of a trade for life, if possible. If it is found after he has begun work that he has no aptitude for that which he has undertaken, an attempt is made on the part of the school principal, the parents, and the employer of the boy to find the kind of work for which he is best fitted. As some one has expressed it:

> Under the coöperative public school system, the grade school principal pays much less attention to biology and much more to the boy.

The second feature is the work of shop coördination. In order to explain this, the method of operation in the Engineering College at the University of Cincinnati will be used as an example.* The coöperative engineering course at the University of Cincinnati is of 6 years' duration. There are, therefore, six classes, and there is one shop coördinator for each class. The shop coördinator is a college graduate acquainted with shop practice. He spends every morning at the university and every afternoon in the shops. His function is to make a direct weekly coördination of the work of the shop with the technical work of the university. This afternoon, for instance, he may be at the shops of a local manufacturing company, where he will observe the student apprentices at their work. He will know what they are turning out, their "speeds, feeds, and cuts," the angle of the tool, how the batch of work is "ticketed," how the work is set up, the power drive—everything important in connection with the operation. Next week these young men will be grouped together with their classmates for two periods in class, when he will explain the functions of the particular articles on which the students were working in the machine which the local manufacturing company builds.

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* This feature is just being introduced and its effectiveness cannot be stated at the present time.

He will take up all questions of speeds, feeds, cuts, accuracy, etc.; figuratively speaking, he will take from the student apprentices the blinders which would restrict their vision except for this explanatory work. The "ticketing" of the batch of work is gone into, the system of shop routing is explained. Ultimately, all problems of shop organization, shop accounting, cost keeping, shop planning, power transmission, heating, ventilating, lighting, etc., are discussed during the 6 years' course. In conjunction with this, a card system is employed, by means of which everything the student does in the shop that exemplifies a theory taught in the university is called in detail to the attention of the teacher of the theory, so that when the student comes to that particular theory the exemplifications which he has had in his practical work in the shop are called to his attention. It will be seen, then, that out of the student's own experience is drawn much of his course in mechanisms, thermodynamics, machine design, strength of materials, etc.

In the coöperative work in the public schools this close and immediate tie is taken up in a modified way. There will be a shop coördinator for such trades as have a fairly close relationship, rather than by classes, as in the university.

Now in order to show the application of the fundamental principle of the coöperative system mentioned above, but with a deviation in detail to meet a special condition, let us consider the department store. Such a course has been devised and is about to be put in operation. The fundamental principle is strictly held to, but the details are modified to suit the conditions. In any department store, the clerks are not usually busy until 10 o'clock in the morning. A store can get along easily with one-half its clerks from 8 until 10 o'clock. It is intended to divide the force into two sections, one-half of whom will receive instruction this week from 8 until 10 o'clock, while the other section is working; the following week the sections will be changed about. In this particular instance the students do not go to the public schools; the teachers go to the store. It is evident that it is easier to transport 20 teachers than to transport a large number of student-clerks. A number of rooms in the store, such as carpet rooms and lace rooms, are set aside during these two hours for the class work, the chairs being removed at 10 o'clock, and sufficient space being reserved for any business which way be necessary up to that time.

It is contended by department store owners that salesmen should know the psychology of salesmanship, and have a fairly expert knowledge of the things they are selling. They should receive, besides, a certain amount of general education. The psychology and the general education are to be taught by trained teachers from the public school system. In order to teach the practical end, the following method has been adopted. Consider, for instance, the shoe department. If one pair of shoes costs $1.85, and another pair costs $1.95, the salesman should know where the difference of 10 cents' value lies. Let us assume that this particular department store buys shoes from a firm in Brockton, Mass. When it makes its next contract for shoes, it will insist that the firm selling the shoes send an expert demonstrator to its store, to explain in detail all the different successive operations in shoe making and all the different elements which make differences in cost. The tanning firm from which the shoe manufacturer buys his leather will be required to send to the store an expert to exemplify practically to the students the different grades of leather in a hide, methods of preparation, and why one kind of leather is used in one part of a shoe, and another in another part of a shoe. It has been found that the shoe manufacturers will very gladly enter into any scheme of this sort. He would in fact be a very short-sighted manufacturer who would not. This same general idea is followed in all of the other departments, such as jewelry, linen, silk, furniture, etc.

Other instances might be cited of experiments now in operation based on the simple principle of the coöperative system, with changes in detail, but the scope of this paper will not permit their consideration here.

It is intended to call particular attention to the fact that under this plan the public school deals with the whole general problem, deals with it without physical equipment. It is, in other words, a return to the old apprenticeship system with something added; namely, definite instruction in efficiency by trained teachers, and additional instruction aiming toward better citizenship.

The writer realizes that many manufacturers will say that a scheme which brings two sets of students into any work on alternate weeks—assuming that the alternate-week system be used—is not practicable, and will result in demoralization. The only answer to this is that three years of operation at Cincinnati, and shorter periods of operation elsewhere, have demonstrated that the criticism is untenable. Two alternating students work very well together and there is no confusion. Emphasis is laid upon this, because before the coöperative system was started this objection was the greatest obstacle in the way of its adoption. Men who were skeptical about this phase of the work have become enthusiastic over the smooth working of the system after a fair trial.

It is with hesitancy that a certain feature of industrial education is touched upon at this point, in view of the many propoganda that are being made in favor of it. There is a belief that there will be a tendency to swing too far in the "practical" direction, and that the impetus now being given to trade education may result in a too material training of the youth of the country, injuring to a certain extent that phase of education which should tend to the training of all civic units for civic service. In other words, the fact that every unit is a citizen of a republic, and that the republic depends for its stability upon the character of the mass, must not be overlooked. Fundamentally and primarily, as stated at the beginning of this article, the training of men to become citizens of a republic must be a vital part of any worthy system.

The object of all education is to make good citizens, and the first duty of a good citizen is to earn his own living. The second duty is to be a good citizen in the civic sense. All education, whether industrial or otherwise, should be directed toward these two very important phases of our national life. Here again is a very strong reason why the whole problem of industrial education should be solved in the public schools, where there will be the check of conservatism as to the character of the work, and where the whole solution will be under the direction of men who are servants of the public, and who naturally and by tradition look upon the problem with the widest and safest vision.

The writer has purposely omitted going into definite details, curricula, etc.; for instance, as to how a student should be instructed in arithmetic, algebra, and chemistry. At the present time these do not constitute the problem, and even if they did, enough work has been done in different kinds of schools to demonstrate clearly the character of instruction which ought to be given. The problem confronting us is the method of comprehensive action for the whole situation in the United States. We cannot adopt the German system, for the simple reason that the social stratification in Germany is horizontal, while in this country it is vertical. That is to say, the problem in this country is to find the highest elevation which any man's ability will permit him to reach, and to get him to that elevation. It must be evident that with this system in general operation in the public schools, admission to the university would be by natural selection. In the future, when the system becomes general, only those men will receive the higher education, who will make the best use of it, and hence will give the greatest return to the State.

The writer believes that the American Institute of Electrical Engineers, a national body of men whose personal interests are dovetailed so closely with the whole industrial welfare of the country, can do nothing better than to stand for a movement involving a broad, systematic, and thorough industrial and civic training under a national system.

DISCUSSION ON "FUNDAMENTAL PRINCIPLES OF INDUSTRIAL EDUCATION." NEW YORK, APRIL 16, 1909*

Harry Barker: All of us, interested in educational problems, welcome any broad exposition of the aims of industrial education, and of the development of courses that will appeal to the good sense and democratic ideals of the American people. It is fortunate that Dean Schneider has diverted our attention from the details of mere "industrial training" to the broader aspects of "industrial education." When we discuss specific curricula we easily get into fruitless disputations over the distribution of attention between cultural subjects and practical training.

We admit the need of improving the schooling of the coming generations, not only of mechanics and artisans, but also of business and professional men. The first group seems to need a better grasp of the possibilities of some trade which will yield a living, a better introduction to certain ideals of that living, and a cultivation of the imagination to illuminate and inspire the ideals. The younger members of the second group need a closer contact with many practical things and more knowledge of workers, and the conditions under which work is actually done.

The broader the view we take of industrial education, the more comprehensive becomes that term, until finally it stands as one expression of a tendency of the whole system of American public school instruction. The educational method of the future seems likely to become, as President Eliot has so well said, a teaching of how to do by doing—not by reading—an education that is more than memory training. In making courses for future mechanics and artisans, the effect on possible courses for future business and professional people may well be considered at the same time. There seems, in fact, no need for a strict classification of the education of such classes.

The poorer a child's parents are, the more utilitarian needs his education to be, that he also may quickly become a breadwinner. This means a most practical equipment for advance at some trade, and a corresponding lesser emphasis on the so-called cultural side. The more money and time there are available for the child's schooling, the greater the attention we can pay to this side, and the later perhaps can we postpone the utilitarian training.

Two ideas should stand out clearly. First, with the poorer children we should not utterly neglect art, literature, civics and the awakening of the imagination to throw color about dull work. Secondly, with the children in better circumstances, we should insist on attention to more manual or industrial training, not stating exactly how or when this should come. This will help to make better citizens, broadminded workingmen, and more sympathetic business and professional people.

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*C. E. Dooley's contribution to this discussion is contained in his paper "The Training of Non-Technical Men," pages 1087-1093, Proceedings A. I. E. E., August 1909.

A few words on the relation of this training to that of the future professional men, especially engineers. Most such young men must attend college. Under the inflexible entrance requirements which we must unfortunately expect for many years to come, these popular industrial courses cannot develop literary, historical, and mathematical subjects to such an extent that a student completing a machinist's course, say, would be admitted to the freshman year of a mechanical engineering school, no matter what his ability and inclination. If ambition urge him on, he must be able to continue under some coöperative plan to complete the studies that satisfy the entrance requirements. The work and study for becoming a desirable wage-earner will help to make him a good engineer, but it cannot prepare him for higher education through the usual channels. Therefore, teachers in all industrial courses need to be especially alert, so that a child who exhibits exceptional ability, inclination, dexterity, and ambition, may be encouraged to aim at something higher than a mere occupation. Perhaps in many cases the poorer boys can be helped to begin a college preparation without the loss of a year or more in first completing the regular trade course. A comparison of actual and proposed industrial courses and of standard college entrance requirements seems to show that this is the only way in which the statement near the close of Dean Schneider's paper may be fulfilled. He says:

> It must be evident that with this system in general operation in the public schools, admission to the university would be by natural selection.

One possible effect of the spread of industrial courses will need to be guarded against; that is, the drawing into wage-earners' courses of boys who do not need to sacrifice the greater benefits of present and future high-school training—boys who do not really have to earn as they study, or who do not have to become wholly self-supporting at, say, 17 years of age. It seems a reasonable rule to impose that every student should be kept from making greater concessions to immediate circumstances than are imperative. The great number of applicants for entrance to the few industrial school courses now in operation seems to indicate such a tendency.

There is one point on which Dean Schneider ought further to inform us. He states that 17,000,000 school-children have to go to work as soon as the law allows them. This is 95 per cent of his estimate of the school-children of the country. In the short time available I have not checked these figures thoroughly, but Dean Schneider's source of information does not seem to agree with the U. S. census reports. In 1900, of all persons in this country 10 to 14 years old, 80 per cent were in school, and of all persons 15 to 17 years old, 42 per cent were in school. The deduction is that less than half the school-children went to work at the minimum legal age. It is noteworthy, too, that these percentages are found 10 to 12 per cent more favorable, to the children in manufacturing states and less favorable in states like Virginia, South Carolina, Oklahoma, and Arizona, where there is less manufacturing. In this connection it is interesting to note that in 1900 only 24.3 per cent of all persons in gainful occupations in this country were in manufacturing and mechanical pursuits. This incidentally supports Dean Schneider's contention that the courses must be broad rather than special, so far as the public school teachers are concerned.

The best educators demand that all possible attention shall be paid to preserving the "play-spirit" of those who come under any scheme of industrial education. It is hard to give them as much training as is needed without filling their days and months so full of work that they lose the opportunity, and later the ability, to utilize those relaxations and recreations that are wholesome and refreshing for the body and the mind. Are we justified in taking a boy of from 13 to 16 years of age, and working his mind and body for six days a week throughout the year, with a scant vacation of two weeks? What comes from the lack of air, sunshine, and fun during the years of adolescence? In reply to such cautions we are often told about the relief and relaxation that come by the mere insertion of class hours between shop-periods. That is undoubtedly true to a certain small extent, but by a little more attention on such a point, the production of a still better kind of "civic units", as Dean Schneider says, will be possible.

The spread of "industrial education" may be slow, but there is an immediate field of work needing attention. Success here will pave the way for the industrial courses. Our schoolboys need *systematic* watching to see what abilities are cropping out; they need to be put to work to prove or disprove the existence of natural bents. Those now best able to exercise such surveillance are teachers in public high schools, but some of us feel that they are not quite properly prepared for giving the most intelligent attention and advice. A great and increasing number are college graduates with some knowledge of the natural sciences, and often having had intimate contact in college with engineering students. Such teachers will be able to grasp the desired methods easily, and they have some excellent pedagogical associations through which they may be reached.

Arthur D. Dean: A great deal of interest is now being taken in the subject of industrial education. It presents a newer phase of education. In the past we have been confining ourselves to the "citizenship" idea, a civic idea which has always held true and always should hold true; but we are bringing in, as we should, the self-supporting and economic purpose in education.

President Butler thinks it is a grave error to set vocational training and liberal training in sharp antagonism to each other. He says:

> The purpose of the former is to pave the way to some appreciation of the latter, and to provide an economic basis for it to rest upon. The

equally grave error of the past has been to frame a school course on the hypothesis that every pupil was to go forward in the most deliberate and amplest fashion to the study of the products of the intellectual life, regardless of the basis of his own economic support.

Dean Schneider says that education is very largely, but is not entirely, a public function. I believe that it is the duty of the state and of local communities to carry on industrial education. Of course private institutions can train their own workmen, but it is primarily the duty of the state to educate its own children. Dr. Draper, Commissioner of Education of the state of New York, says that this plan is the only one which holds out an equal chance to everyone; it cannot, in the nature of things, be left to private enterprise. It cannot be dominated by any forces which are in the least exclusive. American workmen are not willing to depend on philanthropy; they will not widely accept the training schools set up by the manufacturing corporations. They are entitled to much the same rights as those that are already granted to the professional and employing classes. They know that they are entitled to equal educational opportunity and will exact what belongs to them. Whatever is done they want done so completely as to command the respect of the best skilled workmen. They will tolerate no false pretense about mechanical skill, but they will be glad to shorten the time in which their boys may become real journeymen. In any event, they know very well, at least their leaders do, that when these things are so they will have to accept them. All this can come in no other way than upon the basis of, and in association with, the public schools.

The New York State Education Department is encouraging local communities to avail themselves of the new law relating to industrial and trades schools. The state of New York is committed to the policy of industrial education. The Legislature of 1908 passed a law providing for the establishment and maintenance of general industrial and trades schools in cities and in union free school districts. For each of these schools which has at least 25 pupils and employs the full time of one teacher, the state will make an annual allotment of $500.00 to the Board of Education and an additional $200.00 for each additional teacher.

Those that are charged with the carrying out of this law are not committed to any one plan. There are several excellent plans. Dean Schneider's plan is only one; the public trades school, without coöperation with the factory is another. It is too early to prescribe rigid general rules to which all must conform. For the present each community will have to be treated as an individual community, and for some time educational necessity will demand plans flexible in nature, plans that can be modified as the need appears for changes based upon a large experience.

I have spent the last 9 months travelling over the state of New York and have met hundreds of teachers, many manufacturers, and public spirited men and women. I have yet to meet opponents of the new movement. The State Education Department recognizes that these industrial schools must be flexible enough to provide: first, for those that can attend school all day; second, for those that work a part of the time in order to earn a living but can afford to go to school part of the time; third, for those that work all day but can attend school at night.

Industrial education is a new thing to some people in this state. A good many people are asking what the fundamentals are in education and urging that we get back to them. Some school superintendents suggest that the part-time idea is a possible solution of a serious school problem. They lament the fact that large numbers of children are burdened too early with the necessity of bread-winning and that they are forced into it with no suitable general training, and not sufficient mental or physical maturity. A certain number of manufacturers do not seem to favor the part-time idea; they say that they do not want to be bothered with boys and girls who will work but half a day in the factory and go to school the other half.

The technical difficulties in the way of maintaining a half-time system in all lines of industries are evident. I can see how the plan might be successful in Fitchburg, and I can see how it might be a failure in the papermaking and textile industries in New York state.

Probably in the future we will rise to our opportunity either through state laws, force of public opinion, or individual willingness on the part of manufacturers, to have a system of continuation schools similar to those of Germany—a system that will make it possible for the children to be dismissed from factory duties for a few hours a week in order that they may attend public schools and receive training which will make for true citizenship in an industrial democracy. When this is done I hope to see it a part of the scheme of public school education. The problem of industrial education is a public affair. Of course it includes the interests of the manufacturers, but primarily it is in the interests of the workers. I am perfectly willing to see the public schools take the boys and girls a part of the time and to have the shops take them a part of the time; to have the schools give shop mathematics, business English, shop accounts, mechanical drawing, etc., while the private shops give the necessary shop practice. As a public official, I want to know what the boys and girls are doing in the factory; I want to be sure that the work that they are doing is educational, that the shop schemes are educative ones, that the boy is being advanced in his shop training. I expect that the coöperation between the shop and the school will be so complete that the public school authorities will receive reports of what the boys and girls are doing in the factories, how long they are kept at certain machines, the variety of their work. I believe that true co-operation between the public school and the private shop will be worked out only when local or state school officials are allowed to go through the factory and see how well the work is being done from the standpoint of the development of the young worker. The schools can provide the theoretical work which accompanies the practical knowledge, but for the school to do its share without being sure that the factory is doing its share, is fundamentally wrong.

In this matter of industrial education we are in the midst of a great task. We are working out the basis and the details of the greatest industrial democracy in history. Let us lose nothing of our good humor; let us cultivate toleration of opinion; and let us think clearly, with an open mind.

C. E. Downton: The company with which I am associated has made several attempts to evolve a comprehensive apprenticeship system for trade apprentices. We have a two-year engineering apprenticeship course for technical graduates, and a four-year course for the various trades. I shall speak of the latter course this evening.

The proper training of apprentices for the trades is a serious question with us, as it is with all industrial enterprises. A concerted effort must be made to bring about a comprehensive method that will be universally recognized as practicable, else we shall, in the near future, experience a dearth of skilled mechanics and artisans which will place the manufacturers of this country at a decided disadvantage with those of foreign countries, where this matter has been given attention for years. It will not suffice to train men to handle certain machine tools; they must be given a general knowledge of a trade as well as some mental training that will enable them to use the brain to better advantage. They must be taught to guide their hands more intelligently.

The public schools do not meet the requirements of the trades, nor can they be expected to. The problem is entirely beyond the scope of any public school. The factory must therefore assist the schools through coöperative methods, or the manufacturers themselves must establish an educational system supplemental to the shop apprenticeship courses adequate to the mental development required for each particular trade associated with the product manufactured by them.

This condition can only be brought about by an effort on the part of all manufacturers, each carrying his share of the burden. It would not be fair to those willing to spend time and money in the training of apprentices to have others appropriate the benefits. The distribution of apprentices throughout a large works, left to the care of each foreman, will not bring about the desired results. The apprentices must receive closer supervision than can be expected from the average foreman, whose first interest is large production and low cost; for the tendency would be to keep the apprentice confined to one process for too long a time. Increased production, for which we are all striving, does not go hand in hand with the proper training of mechanics; for under these conditions the boy is apt to become a specialist rather than a master workman.

To carry out an educational scheme to work satisfactorily with such a distribution of apprentices is a difficult task. The work is so varied in character, and the boys are so scattered, that the problem is so complicated as to seem beyond solution. The most sensible and the simplest plan is to provide a separate department in the works where the primary object is the proper training of apprentices. The boys should be under the direct supervision of instructors who have been chosen not only because of their skill as mechanics but also for temperamental qualities and knowledge of boy nature.

An educational scheme suitable to the requirements can be carried out without friction or decrease in efficiency of any of the producing departments. An excellent example of such a scheme is that in force at the Lynn works of the General Electric Company described in the paper presented by M. W. Alexander at the Atlantic City convention in 1908.* We have introduced the Alexander system in our works on a small scale, and it has proved very satisfactory. We have not begun the educational part, but we are contemplating doing so in the near future. We have provided school rooms for the purpose.

Chas. P. Steinmetz: In former discussions the Institute has dealt with the problem of college education, and if the college of to-day is superior to the college as it existed in America eight years ago the Institute probably can claim some credit for it. This year the plan was to cover the educational work outside of the college and that preceding the college. While a number of interesting and important suggestions have been received they do not appear to be a conclusive review of this feature of the general educational problem. They cover a wide field, far wider than any the Institute has ever attacked before, so that in discussing the subject perhaps it will be advisable to analyze the situation first.

Society says that safety requires every citizen to have at least a certain minimum amount of knowledge of the subjects important in daily life, and proceeds to supply this knowledge in the education given by the elementary schools. Every future citizen must be made to acquire at least this minimum amount of knowledge. But preferably the citizen should know a good deal more; he ought to be informed on many other subjects. To those who can afford the time this education is given by the high school and the college, and we speak of men who have gained this broader and wider knowledge as educated men. This, however, is not sufficient for the work of life, but in addition to the general education there must be a training in some particular industry.

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* Transactions A. I. E. E. Vol. XXVII. Part II. p. 1459.

If a boy learn the art of brick-laying or boiler-making, we do not call that acquiring an education; it is called learning a trade. If, however, the boy is sent to an electrical engineering school he is supposed to be getting an education. But becoming familiar with electrical engineering is not getting an education; it is learning a trade; and does not differ essentially from the learning of any other trade, as that of machinist. Calling it a profession, is merely giving it a different name. The work of our electrical engineering colleges is twofold: they devote the first two years to completing the general education, and the last two years to teaching the trade—or profession, if this term is preferred, of electrical engineering.

When discussing the education of an engineer, there should be kept in mind these different and somewhat antagonistic phases in the preparation for life's work: 1. The education which gives general information on all subjects on which the human being should be informed, which has the effect of broadening the mind. 2. The training in one particular subject, whether called trade or profession, which of necessity must be narrowing, as it deals with one subject and devotes all attention to that. Though this special training lowers the ability to judge impartially of the relative importance of things, it is necessary because it is impossible for one individual to master the details of more than a very small part of human knowledge. Therefore, in order to reduce as much as possible the harmful effect of its narrowing action, we must have as broad a general education as possible. Now, since we do not call the learning of the trade of boiler-maker or blacksmith an education, we have no right to call the special instruction in electrical engineering, in architecture, etc., an education. The term education can properly be applied only to general and broadening instruction, not to the specific training in a profession or a trade. Though this training is necessary for life's work, it is rather antagonistic to true education.

I agree that it is time now to realize that reading, writing, and arithmetic are not sufficient, that there are other subjects concerning which the intelligent mind—whether it merely receives the elementary education or the education is to be continued to a college course—should know something else, food, shelter, clothing, etc. If this is called industrial education it is legitimate, and probably the educational system of the country should be modified. But the teaching of a trade is not within the purpose of the elementary school: the time of study in the elementary school is altogether too short to withdraw any part from the broadening effect of general education to devote it to the learning of a trade or business. If this be the purpose, if industrial education means converting the elementary school or the high school into a trade school, or a combination of trade schools, it is a serious, a vicious matter.

Let us take up the second subject, the learning of a trade, or the studying of a profession, whichever it may be called. In this the college fails to a considerable extent by being too theoretical; the ordinary apprenticeship fails by being only practical and not theoretical. In learning a trade we must consider that there is both the practical side and the theoretical side. Theoretical knowledge and practical experience are both required by the brick-layer or the boiler-maker as well as by the electrical engineer or the architect. The weak point of our present methods of preparing for life's work is the failure to supply the proper proportion of both theoretical knowledge and practical experience. In the college education, energetic attempts are made to supply the deficiency of practical experience, either by introducing more or less inefficient shopwork in the course, or preferably by an alternation of the theoretical training in the college with practical experience in the factory. The same conditions probably also apply to all the other professions and trades. But the college takes care only of a small fraction of the educational work of the country.

Thus far consideration of all the other educational agencies has been almost entirely neglected by the Institute. It is important for the future development of the country that the various agencies of education should coöperate—the college, the trade schools, correspondence schools, apprenticeship courses, etc., and that the proper assistance is given them by us.

It is only a very small minority of young men that can get a general, extensive education in high school and college. The majority have to learn a trade to earn a living and are confined to the limited education of the elementary school. Where they desire to advance, to get a broader education and learn a profession higher than the trade which they have acquired, they have to look to the trade schools, industrial schools, and correspondence schools. By these an enormous work is being done in the industrial cities of the United States. It is a work that cannot be done by a college. At present we have no systematic provision for the education of young men whose necessities have thrust upon them the need of earning a living. Here the supervision of the Institute should be exerted, and it is the field which I consider offers the greatest promise for the Institute's activities.

W. S. Franklin: Professor J. McKeen Cattell has recently said* that perhaps it would be well for us to "scrap" our entire educational system and organize it anew. Being inclined to the same opinion, I would ask Dean Schneider why he says, parenthetically, that no displacement of the present high-school course is contemplated in his scheme of coöperative industrial education. For my part, I think that the greatest obstacle in the way of establishing industrial education is the school system that is now fastened upon us. The expression "educational mill" has been used by one or two of those who have discussed Dean Schneider's paper; I think it would be more fitting to use the expression "educational windmill"; for I believe that nearly all serious-minded men are convinced that our present system of education accomplishes but little. I do not mean to apply this term educational windmill to a narrow group of educational institutions, but to all alike; and I will attempt to justify the expression by referring to some of my own work.

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* *Popular Science Monthly*, March, 1909.

I have been simplifying my instruction every year for many years. Last spring I taught elementary mechanics to 190 freshman engineering students in the simplest way I knew; in particular, I discussed minutely the practical aspects of work and energy, giving what was intended to be a thorough drill in problem and laboratory work. At the end of the half-year I gave this problem:

> A cart moves due northwards at a velocity of 6 ft. per second. A mule pulls straight northwards on the cart with a force of 90 lb., and a man pushes straight downwards on the cart with a force of 180 lb.; how fast is the mule doing work and how fast is the man doing work?

Of the class, 43 per cent calculated that the man was doing 2 h.p. and the mule was doing 1 h.p. Now I do not consider it the fault of my own teaching that 43 per cent of the class should be so lacking in appreciation of the practical aspects of a problem of this kind. I believe the fault lies in the fact that most of our instruction in elementary school, in secondary school, and in college is too highly elaborated; in brief, that we teachers persistently ignore the plain and simple and fundamental aspects of things. Educators have apparently reached the point where they go through motions and ignore results. I certainly believe that a first necessity in the establishment of an effective system of industrial education is to ignore what professional educators have to say on the matter.

I am one of those who believe that our common-school system should be revised from beginning to end. And I think that the vague idea as to the desirability of "keeping children in school", which has been conceded by nearly every speaker this evening, is ridiculous. This concession does not seem to me to be based upon a clear appreciation of the value of a common-school training; it appears rather to be a concession to popular pride in the common school as a thing which sooner or later is destined to educate all of us so thoroughly that no one will be obliged to work. That very certainly is the spirit of the common-school system of to-day, and it is the essence of the popular belief in the system.

It seems to me that anyone who has a keen appreciation of the tremendous importance of industrial education must thereby have acquired a degree of contempt for our present system of education. Of course no one in his right mind wants to put boys into shops and work them to death—although many men not in their right minds not only wish to do this but actually accomplish it on a grand scale—but young boys must be given something to do that will develop them; that is certain, and many of our most thoughtful men and women are beginning to realize that the common school does not meet this condition.

What, essentially, is any great industrial establishment, the Bethlehem Steel Works, for example, but a school. For unless men are trained to do the work our industries cannot continue. Every workshop and every industrial and trade establishment in the country, to the extent that it is a school, should be used as such. I believe that the proper utilization of the conditions of trade and industry, especially in our populous centers, in a rational system of practical education is the most important educational problem of to-day, and I believe that its solution lies in an intimate coöperative organization of the common-school system with every industrial and trade establishment where boys can be properly employed. In a practical sense nothing has educational value but work, and nothing else but the actual conditions of our practical life can shape the coming generation for their work in the world. It is, I believe, extremely absurd to attempt to elaborate an artificial substitute for industrial conditions in the detached manual training school or in the detached industrial school, except to a very limited extent and as a rudimentary beginning in the initial training of the youngest students.

Many men seem to be shocked at what they consider the materialistic point of view of those who advocate steel-mill and cotton-mill versus windmill education; but let these men consider whether a materialistic point of view may not after all lead us infinitely further and higher than any fanciful system of windmill education.

John Price Jackson: The great educational departure that is being tried at Wisconsin has not been touched upon yet at this meeting, though in many ways it is one of the greatest experiments in education in progress. Under the direction of the state and the University of Wisconsin, Director Louis E. Reber has established extensive courses which are intended to reach all classes of people in all walks of life. Thus the state sends qualified teachers to manufacturing establishments to teach classes of an industrial nature, or to other communities to teach such subjects as may be called for; correspondence, special classes, educational trains, etc.—all are utilized. I do not know the value of this movement, but there seems to be no doubt that it is in the right direction.

The great bulk of our young men and women, after they leave the public grammar school, cannot go to any other school; a few only are able to go to higher grades. My feeling is that, in the early years, the schools must adhere closely to the "three R's" which form good practical education. The pupils must be taught the proper use of the mind, hand, and eye; how to build up a good body; and to appreciate some of the higher expressions of life and thought. *After* such preliminary preparation, ***not with*** it, may come specialized training. Many boys because of environment cannot reach the industrial school. Therefore, to reach those who cannot go to a trade school, send a teacher to the factory, or store, or railroad—give them, as well as the more fortunate, an opportunity to develop. Dean Schneider's coöperative plans are excellent for the purpose, but they must be applied with such judicious care that they will not interfere with the early school work.

I have said a word or two in my written discussion, appended hereto, in regard to Dean Schneider's "alternate week" system for college men: it is only applicable to a limited extent. Thus, in hard times especially, industrial or commercial concerns cannot take all the pupils who must later enter the industries or commerce. The school system must give every boy a chance, and, therefore, it seems to me that in its remodeling care must be taken to do the work in a way so facile that it will meet the different conditions of the various communities and classes with which it has to deal. This will require trade schools, schools in the industries and elsewhere, correspondence courses, and other methods, but little time or thought can be wisely given by the pupil in his early years to other than the general foundation training needed by all children.

Otis Allen Kenyon: Education of the young is the greatest and most important problem with which we have to deal. We may possibly go so far as to say that the answer to the "eternal question" as to the real purpose of life is to produce a better generation than the present ruling one. It is a field of endeavor in which every man and woman can take an important part. The education of an individual begins the day of birth and extends over the entire period of active life. For this reason it is most important that all of the early training should be in the fundamental principles, which may be considered as tools with which all subsequent progress can be accomplished; that is, we must prepare our youth for self-education.

Reading is the first requisite, since I consider that most knowledge is acquired by reading. Broadly considered, training in all fundamentals is simply learning to read. Especially is this true of languages and mathematics. I was astonished some months ago to learn that a large percentage of our American born children did not learn to read, and especially so when I found that New York state stood near the top of the list in illiteracy. The natural conclusion was that the city of New York, with its immense foreign population, was the cause of it. Not so. New York City stands exceptionally high. Illiteracy occurs largely in the rural districts of the state, where there has been no foreign influx for years.

In the Scandinavian and German countries such a thing as illiteracy is practically unknown, and I had previously thought such to be the case here. In New York we have a fine educational system in theory with laws to back it up. The law says that all children between certain ages shall attend school, and having these excellent laws we rest contented, leaving their enforcement to the discretion of local authorities. Therefore, illiteracy is the most powerful where it finds least resistance.

This great problem should be attacked at the bottom and all children given a good start in spite of their local surroundings. Their industrial training will take care of itself if necessary. In former times before industrial training schools were heard of, the hand-workers learned their trade as very few do now. For example, old books made on hand-presses reveal work which we cannot equal to-day with the finest machinery. It is true that a comparatively small percentage of the people were skilled artisans in those times, and, undoubtedly, they were a superior class of men such as we now find doing only brain work. Nevertheless the fact remains that the bread-winner must learn his trade whether he will or not; and if equipped with a fundamental education, he will go further and faster.

Our educational system is not what it should be and the trouble seems to be one that is inherent in our form of government, namely, the lack of centralization of power, and, therefore, a lack of uniformity. The fact is that we have no system.

I believe in individualism in the highest educational institutions, but in the lower ones there should be more and more uniformity as we descend the scale. To say that a boy has a high-school diploma means nothing until we have been told what state the school is in, and even then it really means little unless the name of the city or town is also given. It is a fact that our own colleges recognize diplomas from certain high schools and not from others. With such a state of affairs it is little wonder that the best European schools absolutely discredit all diplomas obtained from our public schools. The first step, then, is to obtain a uniform standard of education throughout the country, so that a diploma of a certain grade has a meaning which needs no special interpretation or explanation.

Granted that we have a uniform and well-organized school system, we can then take up the details of what to teach and how it shall be done. What to teach should be decided by the central organization and should be fixed for each grade. How to teach should be left to the teachers, since no uniform method will please all teachers nor suit all pupils, and no good teacher can work well when using a method with which he is not in sympathy.

The most important thing is to have good teachers. Our teachers should not be reservoirs of knowledge; they should be independent thinkers and natural educators. The whole purpose in education should be to awaken a thirst for knowledge and to encourage independent and analytical thinking. Any youth starting out with the thinking habit and a working knowledge of the fundamental principles of his profession will advance to a limit imposed only by his innate shortcomings.

Dean Schneider's idea of coöperation between employers and educators is an excellent one. The public school cannot teach specialties; it must teach the elements which are used to build up the specialties. However, if the school can follow the pupils into the shops where they are learning their trade and show them how to apply their theory, it can do great good.

As Dean Schneider points out, by far the greater share of our children leave school early to earn their living, and, therefore, the public school should consider them first. They should not be taught many different subjects, but rather be thoroughly drilled in the most fundamental ones. It seems to me that our schools attempt to teach too many subjects, the result being a superficial education which is sometimes worse than none at all. It is absolutely harmful in some cases to teach things which can never be properly comprehended. Many pupils are ruined by education instead of being bettered. They are taken beyond their depth and given a smattering of this, that, and the other; and when they are through they think they are too well educated to learn a trade. Coöperation between schools and employers is a good thing; but what we need most is coöperation in the schools themselves to produce an efficient and uniform system of public instruction.

Dugald C. Jackson: I wish particularly to call attention to the following sentences found in the paper.

> Under present conditions most of the children who leave the public schools go at once into the industries or stores, and there is no connection whatever between school and shop. The children go to work not because they want to, but because they have to become little bread-winners. Here, then, are many children working in some capacity, and a series of public schools carried on only for those who are fortunate enough to be able to continue in their school work. Since the public school system is the only organized institution capable of dealing with all these children at work, and since the children are also learning a trade and earning money sufficient for their simple wants, it seems that the only complete solution of the problem is a system of coöperation between the schools and the factories for efficiency training and civic training of the young people after they have found their work.

This is a clear statement of the present situation, and it emphasizes the fact that industrial training in this country may rest with the public-school system. At this point I wish again to urge the importance of having the organization and development of industrial training put under the direction of adequate educational bodies. When I say *adequate*, I mean bodies that are not only strong in the educational branch, but that are also well informed as to the industrial requirements. I know of no bodies that meet the conditions so satisfactorily as the faculties of the great engineering schools. While it would be a misfortune to have the engineering schools take industrial education into their curricula, such faculties may wisely be held responsible for the organization and development of the work. This is the procedure which is now going into effect in the state of Wisconsin, where the organization and development of industrial education have been placed by the legislature under the direction of the University of Wisconsin, and the work is being carried out by a department of "university extension" of which the director is a well-known engineer who was for a long time dean of one of the engineering schools. This seems to be already bringing favorable results, though the work has been in progress only a short time.

Dean Schneider indicates that the German continuation school idea, which is supported in Germany under the requirements of imperial law, approaches his ideas of the necessities of the present case. In that case the teachers go to the students, as desired by Dean Schneider, but the coöperative or alternating plan discussed by Dean Schneider is not put into effect. Dean Schneider's plan seems to contain the desirable elements of the German continuation school idea, and it adds thereto other elements. To carry out his idea of *in loco parentis* for the public schools would require endless tact on the part of the teachers, and would doubtless call for a higher average grade of men for teachers' positions, in case the plan could be put into effect. But such changes in the teaching staff would be well worth while, provided they brought the results of increased efficiency and improved citizenship for the youths who must bear the brunt of artisanship for the coming generation.

The "coördinator" plan proposed by Dean Schneider is a novel one. It seems likely to be useful; but better results would probably come from the work proposed to be done by the coördinator if he could give his instruction in an extra half hour at noon or at some similar time during the boy's shop assignment. This might be practicable only in the case of establishments employing a large number of the coöperative apprentices. It will be observed that Dean Schneider himself makes a suggestion in harmony with this criticism, in the discussion of the shoe division of a department store.

I believe that this paper presents ideas which are worth the careful consideration equally of the employers of skilled workmen and the public school boards of industrial cities. The ideas are also of vital interest to the engineering profession, for without skilled workmen to execute their projects engineers would be helpless; and the engineers should properly give careful attention to any plans which promise a better training for artisanship.

A. R. Dennington (by letter): As a factor in industrial education the correspondence system deserves attention, not only for what it has done in the past but also for its inherent possibilities. Considered from the standpoint of adaptability, instruction by correspondence is almost ideal, as the student pursues his usual vocation at the same time that he is studying the principles of the underlying theory. It may be implied by some that in the past the student has spent his time studying some line of work entirely different from his daily task and that as a result the correspondence schools were instilling the spirit of discontent and making employes less efficient. Instead of the machinist studying mechanics or something related to his work, he would be spending his leisure time studying bookkeeping or chemistry, with the intention of giving up all his practical experience and making a new start on the foundation of the few unrelated facts which he had learned. It is of course true that an occasional man is able to achieve signal success by such a course, but he must be regarded as the exception rather than the rule. Most persons who take up correspondence instruction have passed the period of life when they can easily make changes in employment, and when such persons do change there is a certain economic loss. It is reasonable to expect that if the energy expended in preparing for the changes in employment had been expended in making the workers more efficient in their original line of work, the measure of their success would have been greater.

There seems to be an almost universal idea in this country that the work of some other individual is more desirable than one's own, and this makes the man who has spirit and ambition a ready listener to any proposition pointing toward imaginary opulence. The man who has spent years in one line of work is unable to judge accurately of conditions outside of his trade. He may appreciate the crowded condition of his trade and may realize the difficulties in the way of advancement, but he does not realize that the same conditions exist in the occupation he thinks of taking up and that individual success in either case involves more than average ability.

The common defects of correspondence instruction as pointed out above are not insurmountable, and will as time goes on be more or less completely eliminated. Statistics show that the greater number of persons who have been materially benefited by a course of correspondence study have read on subjects related to their previous work. They have used their studies as elements in the process of evolution. The usefulness of the correspondence school depends upon its ability to increase the efficiency of the worker in his employment rather than to incite him to make a change. He should be taught the truth that any line of honest endeavor is honorable, that it merits special study and will reward it. It should then be the aim of the correspondence course to make the plumber a man who will do his work with careful attention to underlying sanitary engineering principles; to enable the farmer to produce more from the same soil without impoverishing it; to give the engineer or fireman in a power plant the knowledge which combined with his practical skill will make possible the more economical production of power. In short it is the province of the correspondence school to improve the artisan and thereby cheapen the cost of production while increasing the economic and industrial value of the producer. Training of the kind outlined is narrow in the sense that it is applied with the idea of developing and directing thought along one line, but experience shows that even one small division of any science or art offers problems worthy the most thorough study.

The absence of any personality in the instruction is an inherent defect in the system. This disadvantage cannot be measured because of the diversity of the effect of the personality of any teacher on a number of pupils, and also because of the different individuality of the teachers. Most of the printed lessons represent the composition of several individuals, and an entire course in any branch represents the work of a small army. There can therefore be no pronounced individualism in the courses of instruction.

In correspondence instruction as in regular teaching work the attitude of the student is very important. Many persons take correspondence courses with the idea that their part in the contract is merely to remain passive and receive in some mysterious manner the dreamed of knowledge and power. There is also a noticeable tendency on the part of some to regard the number of pages covered or the number of subjects skimmed as the only essentials to increased efficiency. These tendencies must be considered in forming any judgment of the results obtained by correspondence instruction. In time they may be reduced, but the change must come rather slowly, as many people are willing to accept the superficial and artificial as the thorough and genuine education.

Herman Schneider: In order to satisfy Mr. Barker's question about the figures used in regard to the children of school age in this country, I quote from a report compiled by Professor Ayer of the University of Cincinnati from the Report of the United States Commissioner of Education:

> In 1906–7 there were 24 million children of school age in this country. Of this number
> 76 per cent were enrolled in the schools;
> 54 per cent were in average attendance;
> 18.5 per cent completed the elementary courses;
> 12.6 per cent entered high schools and academies;
> 3.4 per cent graduated from high schools and academies;
> 1 84 per cent entered colleges and universities;
> 0.67 per cent graduated from colleges and universities.

Confusion may exist in regard to the figures I have given previously, because in some instances I state the total number leaving school when the law permits them to do so, and in other cases I state the number leaving school without industrial training. The report of the Commissioner of Education contains the interesting information that out of 24 million of school age about 63,000 children receive commercial or industrial training in the United States.

Mr. Barker is of the opinion that under this system boys would have no time to play, go fishing, roam the field, etc. As a matter of fact, without this system, as shown by the figures given, the majority of the children would be in the shops throughout the year. It is specifically stated in this paper that the coöperative system contemplates taking the children *after* they have found their work, and giving them further schooling. Under the coöperative system the children would be at school at least every other week; they certainly would have play hours and time to roam the fields, which they would not have were they not in school at all. The coöperative system is fairer to the boy than the present industrial system, which shuts him up in a factory nearly all the time.

Mr. Barker further questions my statement that the coöperative system leads by natural selection to the university, saying that a student under the coöperative system would not be prepared to enter the university. Under the Fitchburg scheme, a boy from the coöperative course could enter college after one more year of High School. If he should show an engineering bent in his shop and school work under the coöperative system, he would in all probability be urged to go to an engineering college, and opportunity would be offered by an extra year's high-school work to enter any technical school. If then the technical school has a coöperative system—as a number of them will have—it ought to be evident that the way is open for any ambitious young man of virtually no financial means to obtain an engineering education, provided he ought to have it.

Mr. Dean says that the coöperative system is not generally applicable, that it could not be used, for instance, in the dairy industry of the state of New York. I would call Mr. Dean's attention to an article in the current number of the *World's Work*, which describes a coöperative scheme whereby the University of Chicago coöperates with the large farms in Indiana and Illinois under a plan by which the students work on the farm during the open season, and attend the university during the closed season. There is a definite co-ordination of the theory of the university with the practice of the farm, and this includes the dairy work. It can be shown that dairy work under a coöperative scheme is just as feasible as machine work under similar conditions. The details of coöperation, however, must be made to suit the peculiar conditions.

Mr. Dean also speaks of the difficulty of getting teachers for this system. This difficulty exists in any industrial education system, if industrial education is to be *real* industrial education. The trouble with most industrial education is that it is not industrial, and that it is not taught by teachers who know industries. Teachers can be found if they are sought. The statement is not more of an argument against this system than it is against any other system of industrial education.

Mr. Dean further suggests that if the coöperative system is put into the public schools—and he agrees that it should be—the schools should be given authority to plan the courses in the shops, and that he would insist that his department plan the courses through the shop. I have been operating a coöperative course in engineering for several years, and am not quite sure that I am as yet capable of planning the shop work of my students. The shop superintendent knows more about this than I do. Since the public schools would have to deal with hundreds of trades, it would take a man of greater ability than exists anywhere to plan all these courses in the shops. The shop superintendent knows more about it than any educator. As a matter of fact, these courses are worked out by consultation between the school authorities and the shop people. Coöperation means coöperation; it does not mean dictation by either manufacturer or school.

Professor Franklin asks what is meant by my statement that no displacement of the present high school courses is contemplated, stating that in his opinion the present high school courses should be "scrapped." I agree with him that most of the work of the high schools should be scrapped, and I think it would not make a very valuable pile of junk. What I mean in my paper is that no displacement of the present courses preparing students for the university is contemplated.

Professor J. Price Jackson says that the coöperative system would not be feasible during hard times when the students would be thrown out of work. When such times arrive, it ought to be obvious that under the coöperative system the students are in school at least every other week. If there is no coöperative system, they are idle every week. Between the two, it seems to me that the coöperative system has the advantage. During the periods of depression the student could, if it is desirable, be held in school all the time, and his job reserved for him at the shop until work is resumed. It seems to me that the coöperative system is specially well adapted for periods of depression, in order to have a check on the youth when there is no work.

The purpose of this paper is to point out two things: first, that the problem of industrial education is so big and comprehensive, that it must be solved by the public school system; second, that this must be done by coöperation with the industries for the education of children *after* they have found their work. No arguments have been deduced in this discussion to show that these two propositions have not been established.

The paper attempts to show further that the details for every industry, and for every city, would vary. For instance, the scheme which fits the University of Cincinnati in its engineering college might not fit the Massachusetts Institute of Technology. The details of a scheme that fits the machine industry of Cincinnati might not fit the same industry of Fitchburg, Mass. The details which fit commercial life will not necessarily fit industrial life.

There are many ways in which this coöperation can be carried on. For instance, in the building trades in Chicago there is an agreement between the master builders, the union and the public schools, whereby the apprentices go to school during the slack months in the winter to obtain efficiency instruction. They are not, however, taught the trades in the schools. This is a coöperative system.

The one idea which I am trying to impress upon educators and manufacturers is the necessity for coöperation between the manufacturer and the school for efficiency training and for citizenship training; in other words, to fit the student for the thing he is to do, and for the man he is to be. There is a fundamental difference between a coöperative course in an engineering college and a coöperative course in the trades. In the engineering college, the university selects a number of young men, sends them for a trial period to the shop, where they are finally selected by the manufacturer. In the trades the idea is to take the young men already on their jobs and give them more education. In other words, to take the school to the boy in the shop, and not to take the boy in the school to the shop.

Charles S. Howe (by letter): There are two methods of training industrial workers: through the apprenticeship system and through the trade school. The apprenticeship system is the most obvious and natural method. As the journeyman will work in the shop after he has learned his trade, it seems proper that he should acquire that knowledge in the shop. Manufacturers usually believe this to be the best way because the boy is then under shop conditions while he is learning; he works with experienced men, he gets the shop atmosphere; he learns to do his work so that it will come up to the commercial standard. All this is of great advantage to the young apprentice, and if the conditions are favorable, there is no place better than the shop for learning a trade. It however has some disadvantages.

1 The superintendent may not have a very broad view of the duty of the shop toward its apprentices. If he has not, he will see that each apprentice learns to use some one machine well, and that he remains the greater part of the time at work upon this machine instead of acquiring a knowledge of all the machines in the shop.

2. The smaller shops are limited to one particular kind of work. As a rule it is the coarser kind and hence the apprentice learns only this sort of work. He can not acquire the other parts of his trade in that particular place. Yet under the apprenticeship system he gets at this one place all the knowledge that is required to make him a journeyman.

3. Under the apprenticeship system the foreman is the teacher, but his principal duty is not to teach the apprentices it is to turn out as much work from the shop as possible. When he has spare time he spends it in showing the apprentices how their work should be done. Where the management is sympathetic, where it is the purpose to train the boy in all branches of

the trade, and where a special foreman is employed to teach apprentices, no better system than the apprenticeship method can be found for training the journeyman in any trade.

There are many large establishments which have an admirable apprenticeship system, but the great majority of factories of all kinds do not have such a system, and hence we are not training enough skilled workmen in any of the trades. To meet the demands of the future and to give the boys and girls a better industrial opportunity, it has been proposed to establish trade schools, either under the administration of school boards or under special boards authorized to expend public funds. A few such schools have been in existence for a number of years, and their graduates have been successful. These trade schools, if properly designed and planned, will be in buildings which resemble a shop, will have the same machinery which a first-class shop would have, and the teachers will be men who have been foremen in shops, but who have left their regular work to enter the school because of the higher pay which will be offered. The work turned out will also be of the same kind as that of the shop and will be subject to the same standards of efficiency because it will be sold in the market in competition with other goods. The amount of goods so sold, however, will never be large enough seriously to affect market prices.

The trade school method will train more journeymen than the apprenticeship method. If properly conducted, I believe it will train them just as well as the best apprenticeship system, and in the majority of cases, it will train them better. It will meet the demands of the manufacturers for more skilled workers and it will give the boy or girl who wishes to learn a trade the most complete opportunity of so doing.

V. Karapetoff (by letter): I am favorably impressed with the spirit permeating Dean Schneider's article. There is so much freshness and optimism in it, that one immediately feels new courage and energy for promoting industrial education. The principle of coöperation between schools and industrial establishments ought to be encouraged by all means. The question as to how far it ought to be carried may be discussed later on, when sufficient information and experience will have been acquired.

I am particularly pleased with two ideas in the paper: one is that it is our common duty as citizens of a state or a country to educate the coming generation for a maximum of efficiency; that the duty does not end with paying the school tax. Industrial establishments can help the cause of education by direct coöperation as outlined in Dean Schneider's paper much more and with less sacrifice than by contributions in money.

The other idea is that of interweaving theory and practice so that neither becomes a burden to the student. Practice alone prepares a narrow artisan by its multitude of petty rules and empirical " ways of doing things "; theory alone is barren, being like a form without contents. With the plan suggested, the student is shown how certain results are achieved; at the same time the observed facts are coördinated in his memory by the underlying theory.

G. M. Basford (by letter): Those who are watching the interesting and promising development in the direction of industrial training, and especially those who are in position to realize the great importance of the movement cannot fail to be hopeful of exceedingly important results. This problem is so complicated as to require many different plans for meeting various individual needs. Of all the plans so far suggested, that of Dean Schneider seems to contain the largest number of elements necessary to successful achievements. For large manufacturing establishments producing heavy machinery and involving progress in methods and equipment, progress which at the present time is exceedingly rapid, it is obviously necessary that the school should be taken to the shop. I believe that the plan of Dean Schneider is exactly what is required for such establishments, with one modification, that the part of the development which is generally spoken of as education should in such cases be given at the works of the company. This is going one step further than Professor Schneider has gone.

Alexander C. Humphreys (by letter): The following statements appear in Dean Schneider's paper: "The chief end of education is so to instruct the individual that all individuals as civic units will combine to make the best possible State." . . . "The object of all education is to make good citizens, and the first duty of a good citizen is to earn his own living."

I fully agree that these *should be* the end and object of education, but I am not inclined to believe that we have convincing evidence that these are the end and object of the public school system of these United States. Certainly the results do not furnish such evidence. Some system of industrial education for the training of the masses should be developed to meet this deficiency. At least, the public school system should be remodeled so as to prepare along the lines of maximum efficiency for later specific training for the industries.

As Dean Schneider points out, our public schools cannot be expected to give specific training in all trades, but much can be done in the way of preparation that will apply in a general way to all trades, and more specifically to a few trades. In my opinion, the first step to be taken is in the direction of greater thoroughness in the fundamentals, and especially the "Three R's".

Dean Schneider quotes some one as saying "Under the coöperative public school system, the grade school principal pays much less attention to biology and much more to the boy". I wish this statement could be made truthfully of all elementary public school instruction.

Dean Schneider mentions shop mathematics. The term is suggestive of practical efficiency, but I would like to extend its scope by making it include the simple mathematics required in shop, field and counting house. The every-day mathematics should be better taught in the schools, and especially elementary arithmetic in the elementary schools. I sincerely hope the author is warranted in his belief that the coöperative system can be so developed as to make it generally applicable throughout the United States. Certainly there are great difficulties in the way, and especially in obtaining the coöperation of those engaged in the industries. I fear one trouble that would develop would be the tendency of the professional teacher to attempt to teach where he is not qualified so to do by practical experience. The system to be a final success would have to be the product of evolution, for as yet none of us is capable of preparing the detailed specifications of such a system—we must be satisfied to hold to the good and reject the bad as the practical conditions are met and overcome. In the line of manufacturing, if in any case the green boys and girls could be used to advantage, I should not apprehend any final trouble from the alternating employment of two sets of students. One favorable feature to put against the unfavorable features would be that of incentive to best effort through honest rivalry.

One thing we may all agree upon—in the training for citizenship, and, incidentally, for the industries—our public school system is sadly deficient, and all of us—and we all are concerned either directly or indirectly—should be willing to work as well as talk for reform.

Ralph W. Pope (by letter): There can be no question as to the benefit to the individual, of an industrial education. Even though the person learning a trade may never be required to practice it for earning a livelihood, knowledge of a handicraft will be a source of satisfaction to him throughout his life, especially if he has a natural taste for the particular branch which he has studied and practised. There appears to be, however, considerable doubt as to whether the graduates of industrial schools will follow through life the trades they may have partially learned. A strong social prejudice exists against manual labor, skilled or unskilled, as well as against the confinement and discipline of factory life, which no educational system can overcome. In a comparatively new country the demand for labor of all grades can only be met by immigration. High wages in themselves will not divert the rising generations from their tendency to obtain a livelihood in some other way than working at the bench, not even with the possibility before them of promotion to the grade of foreman or superintendent. Unless some method can be devised to counteract this tendency, the final outcome of industrial education so far as furnishing a supply of skilled apprentices is concerned will simply add to the already overburdened curricula of our public schools.

That this condition of affairs is not peculiar to the present day is indicated by the following excerpt from an essay by Ezra Sampson a minister, editor, and a captain in the revolutionary army. It appears in a school reader published in 1820:

> In the proud and fastidious times in which we live, manual labor of the useful kind is accounted a thing too vulgar for those of the better sort. Many a young gentleman would feel himself dishonored by doing anything called work; and many a young lady would blush to be found employed in an occupation really useful; even though in circumstances imperatively demanding their industry.

It is well to profit by past experience, and for this reason I will refer to the fact that about 1682 Thomas Budd introduced into West Jersey, (the southern part of the present State of New Jersey) the Quaker system of education through which the boys were to be taught:

> Some mystery or trade as the making of machinery, joynery, turnery, the making of clocks and watches, weaving and shoemaking. The girls were to be taught in spinning in flax and wool, the knitting of gloves and stockings; sewing and making all sorts of needle work, and the making of straw work, as hats, baskets, etc.

This system apparently was gradually abandoned, yet I have been told by a neighbor in Elizabeth, N. J. that in his school days (about 1845) the girls were taught shirt-making, and he remembers the teacher's instructions to "fell the gusset to the sleeve, and the sleeve to the gusset." If these "girls" ever made shirts for the family the domestic art has long since been abandoned. About twenty five years ago manual training was again introduced in the public schools of Elizabeth, and has since been abandoned. I asked a pupil of that era if he knew of any instances where the trade learned had been followed after graduation. He could recall but the single example of architecture which is of course recognized as a "respectable" profession. It is evident that a sufficient number of industrial schools have now been in operation for such a length of time as to permit the collection of statistics bearing upon this question, which is: of the number of students learning trades, what proportion have actually followed them in after life?

Sydney W. Ashe (by letter): Dean Schneider's paper discusses the problem of industrial education from a manufacturer's viewpoint. The solution of this problem becomes more difficult where it deals with the employees of an operating company, whose success depends upon all departments moving in synchronism. Where one is attempting to raise the educational status of the employees of an operating company, the work must not in any way interfere with the moving mechanism of the company but must be carried on at such times, afternoon and evenings, as the men are free from their regular hours of duty. The work must be flexible, as the ages of the men range from 16 to 60 years, and their education ranges from that of the grammar school to the college graduate. The work must be attractive, for with the meetings of various other societies, especially in the large cities, the men will not take advantage of such courses and will not attend.

The course must be progressive each year, as there are a certain number who constitute the backbone of the course, who attend almost every lecture, and who must therefore be given first consideration. Most of the men are handicapped by a lack of advanced mathematics which must also be considered. Educational courses for their employees are now being carried on by the New York Edison Company, the Edison Illuminating Company of Brooklyn and the Edison Electric Illuminating Company of Boston, all of which the writer had the privilege of instituting. The method used in carrying on this work was described in detail in the *Electrical World* of May 16, 1908; briefly, it consists in giving an extensive course of experimental lectures on electrical engineering.

The first year a course is given extending from the elements of magnetism through direct and alternating currents. At certain intervals in the course, radical departures are made from the regular program, Table 1, by the insertion of lectures such as on turbines, for the purpose of arousing fresh interest. The second year the subject of fundamentals is dropped for the time being, and the application of the fundamental principles to the company's methods is taken up. A course of such lectures extends from the coal pile to the consumer. A third season, more advanced principles may be taken up.

TABLE I.

CALENDAR OF DATES AND TOPICS. 1909.

1. Thursday, Jan. 7. Magnetism.
2. Thursday, Jan. 14. Electromagnetism.
3. Thursday, Jan. 21. Electrolysis. Electrolytic corrosion. Storage-batteries.
4. Thursday, Jan. 28. Electromagnetic induction. Theory of the dynamo.
5. Thursday, Feb. 4. Practical management of shunt motors.
6. Thursday, Feb. 11. Practical management of series motors.
7. Thursday, Feb. 18. Steam engines and steam turbines.
8. Thursday, Feb. 25. Underground conduit systems.
9. Thursday, March 4. Voltage regulation.
10. Thursday, March 11. Ohm's law applied to distribution problems. The three-wire system.
11. Thursday, March 18. Ohm's law applied to electrical measurements. Ammeter, voltmeter and galvanometer methods.
12. Thursday, March 25. The physics of light.
13. Thursday, April 1. Arcs and arc lamp mechanisms.
14. Thursday, April 8. Incandescent lamps.
15. Thursday, April 15. Principles of recording wattmeters.
16. Thursday, April 22. Elementary principles of alternating currents.
17. Thursday, April 29. Alternating currents continued.
18. Thursday, May 6. Transformers.
19. Thursday, May 13. Alternating current motors.
20. Thursday, May 20. Synchronous converters.

The writer had constructed a special form of projecting lantern with large condensing lenses which could be quickly connected during a lecture from a horizontal to a vertical lantern, also a special projecting galvanometer having a transparent scale, which could be placed directly before the lantern. The galvanometer can also be used with shunts as an ammeter; with resistance, as a voltmeter; with a thermo couple attachment, it will indicate temperature; and with a speed tachometer it indicates speed, all of these being readable on the screen. For alternating-current work new forms of projecting wattmeters, ammeters and voltmeters have been built for the writer. With this combination it is possible to perform on the lecture table and screen, any experiment which can be performed in the laboratory. In two lectures, for instance, it is possible to perform all the experiments of simple electrical measurements given in 20 afternoon sessions in college, provided the constants be properly chosen. The writer, for instance, has projected a voltmeter reading on the screen and in 25 minutes gone through all of the calculations and with a standard cell and potentiometer calibrated the voltmeter directly before the men. This, however, is an extreme case, although the Wheatstone bridge, the Thomson double bridge, and similar apparatus are demonstrated.

In connection with the lecture course a syllabus is printed and distributed to the men, giving for each lecture an outline of the ground to be covered (see Table II.) This syllabus also gives directions for study so that auxiliary reading may be carried on from week to week. In addition to this weekly bulletins are posted calling attention to the lectures. After the lecture the men are free to ask questions, to come forward and examine the apparatus, or to make any suggestions in connection with the course. The lectures are given weekly, afternoon and evening, so as to afford all an equal opportunity to attend.

This work was started three years ago by the Brooklyn Edison Company, which has continued it each year since. Two seasons have now been given to it by the New York Edison Company and this year is the first season for the Boston Edison Company. This year the work was expanded by the New York Edison Company, which has been giving a course of laboratory work and a course of talks by various professors and designing engineers as well as the experimental lectures.

As this work has now been carried on for three years it seems proper to ask whether it has been a success and wherein have the various companies benefited. Increased loyalty of the men to the companies has been the first great benefit of this work. The personal interest of the managements has created in the men a very kindly spirit and a feeling of pride in the home company. The men have felt that the company has been endeavoring to raise their technical standard so that they could advance, and in time occupy positions which now have to be filled from outside talent. The question may be asked as to whether this work would not in time serve to make the men discontented, whether they would not feel that as they had attended all the lectures for a season, they should immediately be promoted to such an office, for instance, as general manager of the company. While it is true that a little knowledge is sometimes a dangerous thing, our results show that a little knowledge in this case has served more to whet the appetite of the individual, and make him realize his own limitations. The men have become more earnest, more inquiring, less mechanical, have read the technical papers more, have kept the librarian busy, have purchased many technical books and have kept themselves busy.

By having a better understanding of the work in which they are engaged, the men are better able to handle their apparatus, a mistake in the use of which, due to lack of knowledge, might sometime result in damage far greater than the cost of a season's lecture course. The men have also been taught to appreciate the danger which is always present, and to use due caution at all times, particular points of danger being emphasized. As 90 per cent of the accidents which occur are due to negligence or lack of knowledge, it is realized how important it is that a man should have as thorough a knowledge as possible of the particular apparatus with which he has to deal.

The men have also been taught to think quickly, which is a valuable asset in times of emergency, especially in the lighting field where continuity of service and close voltage regulation are all important.

Considering the many adverse factors attendant upon work of this kind, its success has been phenomenal. The attendance at the lectures of the New York Edison Company last year totaled slightly under 6000 men. The Brooklyn Edison Company this year had an average attendance 60 per cent better than last year. Out of 13 evening lectures given so far this year, out of a course of 20 for the Boston Edison Company, the average attendance has been 166 men. A slight fee has been charged in Boston for the entire course, and by slightly increasing this fee another season it is hoped to make the course entirely self-supporting. In New York and Brooklyn the course this season has been free to all employees. In Boston the same method was considered but it would have been impossible to have accommodated in the lecture room all who would have attended. As it was, for the first six lectures the seating capacity was taxed to its utmost.

TABLE II.

LECTURE NO. 5. FEBRUARY 4, 1909.

The Practical Management of Shunt Motors.

Preliminary.

Slide showing simple dynamo.
Slide showing windings of shunt motors.

Magnetic Circuits of Field of Shunt Motor.

Parts of enclosed motor.
Field winding has high resistance.
Armature winding has low resistance.
Resistance values determined with ammeter and voltmeter.
Way of connecting field winding to circuit.
Short-circuit current.
Polarity of field coils.
Change of direction of current through field coils causes change of polarity.
Way of determining whether or not field coils are properly connected.
Self-induction of field coils; danger of opening field circuit.

Magnetic Circuits of Armature of Shunt Motor.

Loop of wire and development of armature.
Magnetic circuits of armature.
Formed coils and spacing of same.
Various armature windings.
Change of polarity of armature circuit caused by changing direction of current flow.
Magnetic circuits of armature and field, cause of rotation.

Starting of a Shunt Motor.

Diagram of circuits.
Excitation of field coils.
Precautions to be observed to prevent opening of field circuit through body.
Connecting lamp board in series with armature causes rotation when field coils are excited.
Use of starting box.
Starting current of motor shown on screen.
Function of overload release.
Function of magnet arm on starting box.

Changing Direction of Rotation.

Change of field terminals.
Change of armature terminals.
Change of both armature and field terminals.

Speed Variation.

How to connect in field rheostat. Value of its resistance.
How to tell whether resistance is " all in " or " all out."
Variation of speed, measurement of values, change of field current.
How to tell from starting box when field current is open at starting.
Precautions against starting motor with all of the field resistance in circuit.
Theory of speed variation.

Location of Trouble.

Motor will not operate. Why?
Defect may make itself evident at first glance.
Bearings, clearance, brushes, broken terminals, etc.

Note: With light fuse in circuit turn on starting box first few points and let it come back.
If it flashes, but machine does not rotate, field circuit may be O. K.
If starting box smokes or machine runs very fast, field circuit may be open.
When machine is operating, if commutator flashes as it goes round it may be a high bar, a short-circuited coil, or a hard spot in the brushes.

DIRECTIONS FOR STUDY.

See Swoope, pages 393 *to* 414 *inclusive.*
See Thompson's Elem. Lessons, pages 448 *to* 455 *inclusive.*
See Sheldon, pages 185 *to* 207 *inclusive.*

Franklin Phillips (by letter): Twenty years ago at least, a change was observable in the skill of mechanics working in the engineering trades. This change was slow at first, but has rapidly increased, owing to the passing away of the old-time mechanics who were trained by long apprenticeships to become skilled workmen. Their ranks were still further depleted through the promotion of these men from the bench and machine to positions of foremen and managers of works, those having ability to handle men and the ambition to seek a higher paid position thus being able to obtain the managerial prizes.

The advent of the handy men and the introduction of automatic machinery have led many manufacturing concerns practically to abandon the apprentice system. This has led to a constant diminution in the ranks of skilled workmen, until now the whole country has become sensible of its dependent position as a manufacturing nation and is looking about with its hands in the air crying for help. A service of three years with that able instructor Professor Sweet (and later a four years' apprenticeship, in the Whitworth School, followed by work at the establishment with which I am connected) may have prejudiced me too strongly in favor of the old-time apprenticeship, but I often recall the words of my good father when I had complained to him of the irksomeness of running a screw-cutting lathe or

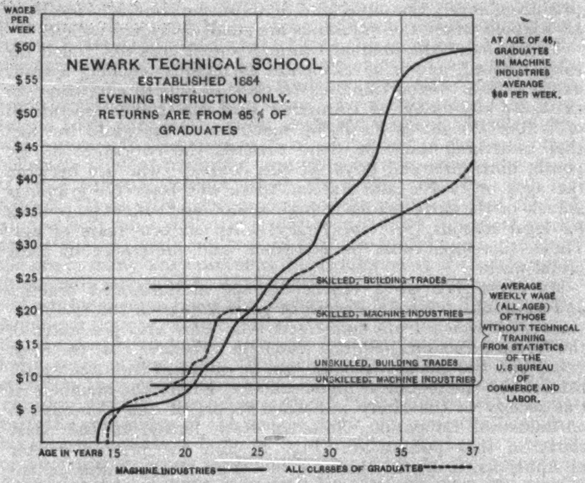

FIG. 1—The money value of industrial training.
Compiled by New Jersey Commission on Industrial Education.

some equally dull operation, he had soothed me with the words—"My son, you must remember that there is no royal road to knowledge", and so I believe to this day there is no short-cut method of making skilled mechanics.

Engineering establishments must get back to the old-time system of apprenticeship, and whether the trade unions like it or not, (they at present put limitations on the number of apprentices employed), sufficient numbers of apprentices must be installed to meet the needs of each particular establishment. This plan works out automatically, as but a limited number can be handled by any one establishment at a given time. The part-time system of Dean Schneider may have undoubted advantages in some localities and would seem particularly well adapted to cities or towns where there are a number of industries producing nearly the same kind of an output, but may not be at all adapted where the industries are small or widely varied.

To my mind the manual training school does not touch the subject at all, and is as elemental as regards teaching a trade as the primary department is to the full college education, or the boy's kite flying as compared with the skilled operations of Wilbur Wright in his flying machine. I recognize the fact that something must be done towards the education of the youth, both girls and boys, of this country, who are between the ages of twelve and sixteen, those who leave the grammar schools or the early grades in high school, and cannot go to work for legal reasons (in New Jersey) until sixteen years of age. These, therefore, must be educated, and preferably in some useful work.

My experience as a teacher in the old-fashioned practice and as an observer of the work of graduates from the establishment with which I am connected, who were also graduates of the Newark Technical School, leads me to believe that the most value and the quickest results can be obtained from the establishment of the technical night school. I refer the members of this society to the lately published report of the Commission on Industrial Education, State of New Jersey, to the chart shown in that publication [Fig. 1], and the printed matter of Appendix C. under the title of "The Money Value of Industrial Training." Professor Colton, dean of that faculty, shows that it costs but $42.00 per capita per year to educate the pupils, while the average wage of the graduates at the age of 45 has risen to $60.00 per week from a basis of $20.00 per week, the average wage of a skilled mechanic.

Do not think for a moment that in educating your apprentices you will increase the available stock of more highly educated machine hands or vise hands, for you will not see them again in this capacity, and this condition will prevail until the demand for foremen, superintendents and office engineers is met and the surplus, if any, for lack of employment must seek the old positions. My thought is, that the trades can be best taught in the engineering establishments, while the schools, either day or night, to my mind preferably the latter, for the time being, will teach the things requisite and not dwelt upon during the course of daily work.

John Price Jackson: The writer highly appreciates such experimental work in pedagogics as is being performed by Professor Schneider and some others in this country. He believes that much good is coming therefrom, and that certain pedagogic principles are being developed which have in the past lain more or less dormant. The writer, however, is not willing to support the tenets of Professor Schneider's faith in all particulars. It is a very grave question whether the average boy can to the best advantage take his college training week in and week out. Indeed, the number who can do this is probably so small as to make the system narrow in its application. Assuming that the college does run in part on a basis of a few days in college, then a few days working for some industrial establishment and so on, it is readily seen that the teaching force and schedule arrangements of studies become difficult and expensive. It must further be noted that students who take their college work in this way, have, in a sense, two masters, and that they lose a large part of the most desirable element of college life which goes with class organization, active part in class and other collegiate student functions, and, to a certain extent, the effect of close personal contact which the college boy has with his fellows. It is recognized among college pedagogs that first of all the boy must daily do good, sound, hard, practical work, and it is also clearly understood that the associations of college life are in many ways useful in the development of the character of the man who is to be of the greatest value to his community.

I am inclined to favor the proposal of Mr. Fred Taylor of the American Society of Mechanical Engineers, who is now offering to take men immediately after the freshman year into his shops for a term of one year. Following this, he expects them to complete their course in college, going to his shops for the long vacation periods. He believes that in this way, he will not disturb the continuity of the college work, nor seriously handicap his shop organization, but that he will obtain the boy at a period of his training, when he is most susceptible to the proper industrial spirit. I agree fully with Mr. Taylor's view, but would prefer to have the boy spend the year in the shops between the junior and senior years in college, and after graduation spend another period in the shops, or other industrial establishment for further perfection and development of his practical ability.

Professor Schneider has insisted that it is impossible for a boy to gain good practical experience in college. To a certain extent, this may be true; but by employing men as teachers who have had successful engineering experience, by bringing in industrialists as professorial lecturers for a few weeks at a time; by having frequent individual lectures by men of prominent success in the industrial world, and by having the technical school of the university directly under the supervision of a committee of successful industrialists, it is undoubtedly possible to so arrange the teaching, and courses, and life of the student that he can be filled with a proper professional spirit and pride in his life's work, and gain a true measure of his own value and worth in practical usefulness. All of these measures are being tried to a certain extent in the college with which the writer is closely associated and are seemingly working to excellent ends.

The author's contention that men, who are by nature unfitted for the engineering professions, are too frequently graduated from technical courses, has some foundation. Nevertheless, if the men at the head of the technical schools use sufficient pains to inquire into the characteristics of their freshmen and sophomores, and to eliminate those unfitted, such criticism need not long continue.

One of the greatest lacks to-day in our technical courses is undoubtedly the absence of sufficient regularly scheduled training in shop or industrial systems, and in the handling of men. This criticism has come to the writer from managers, presidents, and many others prominent in forwarding industrial enterprises. To correct this weakness, the writer has prepared and introduced into the curricula of one college, a course which is intended to give an excellent foundation, and at the same time prepare along the more specific lines required by the manager or superintendent. The course is identical with the other engineering courses in the freshman and sophomore years, including in the latter year, industrial history. In the junior and senior years, in addition to the fundamental engineering subjects of applied mechanics, materials of construction, heat and heat engines, structures, design, shop practice, applied electricity, geology, etc., are given courses in modern language—5½ years, including entrance. Shop systems, shop economics, factory planning, contracts, principles of economy, labor problems, and logic are included. If the criticisms of employers of technical graduates are well founded, this course should perform an important and valuable function, and should mark a direction toward which colleges should aim.

Willard S. Atkinson: Industrial education, in my opinion, should begin in the schoolroom. I have seen many instances of men who gave every evidence of developing into the best of mechanics through shop training, come to a full stop in their development, on account of lack of knowledge of the fundamentals underlying their work, or lack of mental training which would enable them to acquire such knowledge for themselves. To my mind much of the time now devoted in our public schools to subjects of purely academic interest, or entirely useless ones, could with profit be assigned to the study of elementary physics, mathematics and chemistry, and, it goes without saying, mechanical drawing. The embryo mechanic or industrial worker, whatever be his field, will find that there will come a time, in the course of his development into a high-class worker in his field, when the knowledge thus attained of these subjects will seem to him the handiest tools he possesses. In this age of huge industrial enterprises and of immense and costly shop equipments, any attempt to duplicate the essentials of the aggregate of these must appear very meagre indeed. So why not devote all the time that can be made available to the boy, while he is at school, to a thorough knowledge of the underlying principles of the sciences on which the modern enterprises are based? Then when he leaves school and applies for a job, he at least has a foundation under him on which to build, and a mental training of the right kind that will help him to think. For in this age of automatic devices, and huge and intricate machinery, the industrial worker's value to his employer is becoming less and less dependent on his manual ability, and more and more on his knowledge of the work in hand and his ability to think.

The humble petition
of Joseph Jenks

To the Honord Governor with the rest of the
Magistrates and Deputyes now
assembled at the Generall Court
in Boston the 16th of 3d mo
1646

Humbly sheweth unto this honrd Court that whereas the Lord hath beene pleased to give mee knowledge in making and ordering of Engines of Mills to goe by water for the speedy dispatch of more worke with few mens labour in little tyme my desire is to improve this talent for the publike good and benefit and service of this Country, to which end my intent and purpose is (if God permitt) to build a Mill for making of Sythes, and also a new invented Saw mill, and divers other Engines for making of divers sorts of Edge tooles, whereby the Country may have such necessaryes in short tyme at farr cheaper rates then now they can, Now yor petitioner doth humbly beseech this Honored Court that you would please to Grant unto him this priviledge, and to order that no other person shall sett up or use any such new Invention or trade for the tearme of fowerteene yeares without my licence, which hath beene the usuall priviledge and liberty graunted by the high Court of Parliament in England to men that doe invent things of this nature, least after your petitioner have spended his estate, study, and labour, and brought things to perfection, strangers when they see it, may doe the like, and soe I loose the benefitt of that I have studied for many yeares before, which will tend to my great damage if not my utter undoeing, But if this Honord Court shall please to order it accordingly, yor petitioner shall bee incouradged forthwith to sett on the worke and shall have cause ever to pray —

[illegible] of the experiments [illegible]
[illegible]
[illegible]
[illegible]
[illegible] this petition is granted [illegible]
power of the Court to restraine the exportation of such manufactures
& the prices thereof & moderate if occasion so require

Jo: Winthrop Govr
Consented to by ye Deputs
Edward Rawson

To the Honrd Gouernor wth the reſt of the
Magistrates and Deputyes now
Aſembled at the Generall Court
in Boſton the 10th of 3d mth
1646

The humble petition
of Joseph Jenkes

Humbly showeth vnto this honord Court that whereas the Lord hath beene pleaſed to giue mee knowledg in Makeing, and erecting of Engines of Mills to goe by water for the speedy diſpatch of much worke with few mens labour in litle tyme my deſire is to Jmproue this talent for the publike good and benifitt and Seruice of this Country; to which end my Jntention and purpoſe is (if God permitt) to Build a Mill for making of Sithes; and alſoe a new Jnvented Saw Mill, and diuers other Engines for making of diuers ſorts of edge tooles; wherby the Country may haue ſuch neceſſaryes in short tyme at farre cheaper Rates then now they can; Now yor petitioner doth humbly beſeech this Honoured Court that you would pleaſe to Grant mee this priueledg; and to order that noe other perſon shall sett upp or vſe any such new Invention or trade for the space of fowerteene yeeres without my licence; which hath beene the vſuall priveledg and liberty Granted by the high Court of Parlayment in England to men that doe firſt sett vpon workes of this nature; leaſt after your petitioner haue expended his eſtate, ſtudy, and labour, and haue brought things to perfection; Another when hee ſeeth it, maketh the like; and soe J looſe the benifitt of that I have ſtudied for many yeeres before; which will tend to my Great damadg if not my vtter vndoeing; But if this Honrd Court shall pleaſe to order it aboueſayd; yor petitioner shall be Incouradged forthwith to sett on the worke and shall haue cauſe euer to pray—

The Magiſtrates conſidring the neceſſity of raiſing ſuch manufactures as are mentioned in the Pet: & being ſufficiently informed of the ability of the Petitionr to pform ſuch workes: doe conceive it fitt (wth relation to the Deptyes concurrence herein) that his Petition be granted, ſo far as concerns any ſuch newe Inventions: & ſo as it ſhalbe allwayes in the power of this Court to reſtreyn the exportation of ſuch manufactures & the prizes of them to moderation if occaſion ſo require.

Jo: Winthrop: Govr   Conſented to by ye Deputs
Edward Rawson.

Translation of the Petition of Joseph Jenkes and Grant of the First Patent in America for an invention of Apparatus; May 10, 1646, O. S.

Records of the Colony of Massachusetts Bay; Vol. 59, p. 26.

The endorsement at the bottom of the Petition by Gov. Winthrop, representing the Magistrates, and Edward Rawson, representing the Deputies, constituted the Grant, or original official record of the action taken by the two houses of the General Court in response to the Petition.

A paper presented at the 26th annual meeting of the American Institute of Electrical Engineers, New York, May 18, 1909.

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THE PATENT SYSTEM IN ITS RELATION TO INDUSTRIAL DEVELOPMENT*

BY FREDERICK P. FISH

In an address at Springfield, Illinois, delivered in February, 1860, Abraham Lincoln said:

> I have already intimated my opinion that in the world's history certain inventions and discoveries occurred of peculiar value, on account of their great efficiency in facilitating all other inventions and discoveries. Of these were the art of writing and of printing, the discovery of America, and the introduction of patent laws.

While other episodes in the history of the human race might well be added to the list, there can be no doubt that Lincoln was right in including the introduction of patent laws as an incident of prime importance. As he states later in his address —"The patent system . . . added the fuel of interest to the fire of genius in the discovery and production of new and useful things."

Progress has largely consisted in the recognition that things were wanted, and in the supply of them. Each success in meeting a want has led to an extension of the desires of man in a constantly widening circle. The inventors large and small have performed two functions. They have recognized the wants of the community in many cases before those wants were definitely apprehended, and they have supplied what was required or desired. They therefore stand in the front rank of those who have advanced the race.

It does not detract at all from the obligations which we owe the inventors, that they have dealt primarily with material, as distinguished from spiritual and intellectual progress. As a practical matter and in the long run, the latter are impossible without the former. Those who have advanced the industrial interests of man by increasing his control of the forces of nature, and teaching him how to apply those forces to shaping and transforming the raw materials which are available for our use, have supplied a necessary foundation not only for the physical needs of life, but also for that intellectual, moral, social and imaginative development which we all recognize as upon a higher plane than material well-being.

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* Through the courtesy of Mr. W. J. Jenks, one of our members, I am able to present to you a copy of an application for a patent made by the founder of his family in this country, Joseph Jenkes, to the Legislature of Massachusetts in 1646, and a copy of the grant made on his application for what is undoubtedly the first apparatus patent recorded in American history. It is interesting not only as illustrating the form of patent grants more than 250 years ago but because of the admirable quality of its English. A photographic facsimile and a line-for-line transcript in the quaint language and spelling of that time appear side by side as a prefix to this paper.

Much may be said as to the evils arising from the complexities of modern life, and in favor of the simpler conditions of former times. It may reasonably be argued that the extraordinary material progress of the last few years has resulted in a development to some extent one-sided. If such is the case, we need only to be patient, for the underlying forces of society will surely bring about the necessary readjustment of conditions when there has been time for the instinctive and automatic operation of those forces to correct the situation to the necessary extent. And the race will never lose the added comfort, the control of disease, the increase in the length of life, the startling economies in production and the wonderful facilities for intercommunication and transportation, bringing all parts of the world so closely together in thought and effort, which have resulted from our more recent inventions and discoveries.

There can be no doubt as to the validity of the view that has always prevailed, that material progress, although not in and of itself the highest goal to which we should aspire, is of underlying importance to our welfare.

It is no wonder, therefore, that the inventors and discoverers, who have enlarged the power of man to utilize for his own well-being the forces and materials of nature, have been generally recognized as great benefactors. In Mr. Walker's standard book on patents, he quotes the following from one of the early works of Lord Bacon:

> Now among all the benefits that have been conferred upon mankind, I discover none so great as the discovery of new arts for the bettering of human life. For I saw that among the rude people of early times, inventors and discoverers were recognized as gods. It was seen that the works of founders of states, law-givers, tyrant destroyers and heroes cover but narrow space and endure for but a time, while the work of the inventor, though of less pomp, is felt everywhere and lasts forever.

Not only was the work of inventors and discoverers in the old days rewarded by recognizing them as gods after they were dead, but it was appreciated during their lifetime, and was encouraged by the ordinary forms of compensation by which all services to individuals and to the community are recognized. Inventors and discoverers were rewarded by the respect and admiration of their contemporaries as well as by more material advantages. As was but natural, such rewards were in the first instance bestowed by the immediate beneficiaries out of gratitude for services rendered. The idea of definite stimulation to such service, which is at the basis of modern patent systems, did not become consciously recognized until a late period of history.

Not until the 15th century of our era do we find any attempt to reward an inventor by the grant of a limited monopoly of his invention, and even then it is doubtful whether there was in such grant any definite conception of encouragement for future effort, as distinguished from reward for value already received. Moreover, social and governmental conditions were such that it is not impossible that such grants were based upon favoritism as often as upon any principle of justice or sound policy. When we find what was the equivalent of a patent granted in 1467 for the manufacture and sale of paper in Berne; another two years later in Venice for a privilege, exclusive for 5 years, of practising the trade of printing; another in 1507 in Venice of 20 years duration for the introduction of a process of mirror making, and a 10-year monopoly granted in France in 1551 for the same art, it is not at all clear that these isolated cases even foreshadowed our modern patent systems, in principle or in theory.

In England, however, toward the end of the 16th century, we find a rather definite recognition of the underlying basis of the patent system of to-day; but in so far as the sound, modern principle was apprehended at all, its conception was vague, and in its application it was confused with other ideas of governmental interest in, and control of industry, that were for a time, inconsistent with sound development.

The regulation and control of industries had been practised in England for many centuries. While charters had established artificial rules for the management of the different trades through the borough organizations, the guilds, and otherwise, at least as far back as the reign of Edward III what were in effect industrial patents had also been granted for the purpose of inducing foreign workmen to introduce new arts into England. In this way, Flemish cloth-makers, German armorers, Italian glass-workers and French iron-founders were persuaded to establish new industries in England with the hope of royal patronage. These new workmen established their industries side by side with those already existing and to some extent in competition with them. The entire system was one of regulation and control, and only to a remote degree foreshadowed the patent system that was to come. Most of the grants in these early days were to a large extent local in character. They were effective because England, almost alone among the civilized nations, had a government that was really national in its character, recognized and dominant throughout the land.

When the reign of Elizabeth began, the conditions were favorable for the adoption of a real patent system. That great Queen and her advisers were earnestly interested in the industrial welfare of the country. There was a fair degree of economic unity. The guild regulations were already declining. The field was open for development upon new lines.

The earliest recorded application for an exclusive patent of almost the modern type was in the year 1558. It was for the introduction of a new art into England and was presented jointly by an Englishman and an Italian. The petition was granted in 1562 as a "reward of diligent travail" and "to give encouragement to others," the precise grounds which justify the issue of patents under the patent systems of to-day.

At about the same time, another Italian presented a petition explaining that he had invented certain furnaces and "wheel machines" which others would copy without remunerating him unless he was protected. He prefaced his application with the suggestion that "nothing is more honest than that those who by searching have found out things useful to the public should have some fruits of their efforts and labors, as meanwhile they abandon all other modes of gain and are at much expense and inconvenience and often sustain much loss." This again is a statement which expresses the point of view and the experience of the inventors of the present time.

Prior to 1570 not less than twelve patents were granted in England for chemical products and processes and six for mechanical inventions. It is interesting to find these patents dealing with the familiar subjects matter of salt, alum, saltpetre, oil, glass, cloth, dressed leather, and machines for dredging, draining and grinding. Soon afterwards there was issued a patent for sailcloth and one for playing-cards. From that time to the present, letters patent have been granted continuously in England as a reward to the inventor and an encouragement to others.

But the situation was not yet crystallized. The power to grant patents, where it was for the public interest that they should be granted, gave the opportunity to establish monopolies which were distinctly hostile to the public good. Elizabeth and her successor, James I, issued many such patents and licenses analogous to them. Many of them were given to favorites. Some of them were issued solely to increase the revenue of the King, who attempted to exact large compensation for the grant. Instead of dealing only with the question of new industries, many of them were issued for the control of those that were well established. Some were in a way the equivalent of a modern protective tariff. Others were ostensibly based upon the necessity of regulating the quality and character of the product. Some of them amounted to but little more than an excise tax. All through this period, however, the encouragement of invention and the introduction of new industries were regarded as of prime importance, and while the monopolies granted by royal authority formed a constant source of trouble, leading repeatedly to conflicts between the King and Parliament, no one questioned the soundness of a public policy that obviously stimulated industrial development. In a leading case of the utmost interest, decided in the year 1603, in which the court held that a patent granting a monopoly on playing-cards was invalid, the successful counsel, who contended strenuously that such a monopoly as the one before the court was contrary to English law, said in his argument.

> Now, therefore, I will show you how the judges have heretofore allowed of monopoly patents—which is that when any man by his own energy and industry or by his own charge and industry, or by his own wit or invention doth bring any new trade into the realm, or any engine tending to the furtherance of a trade . . . that never was used before, and that for the good of the realm: that in such cases the King may grant to him a monopoly patent for some reasonable time, until the subjects may learn the same, in consideration of the good that he doth bring by his invention to the Commonwealth, otherwise not.

It is interesting to note that in this case an argument for the validity of the monopoly was that playing-cards were merely a "vanity"; that card playing involved "the vices of deception by servants of their masters, and the employment of time that ought to be devoted to other interests and not to such enormities" and that therefore "the Queen might prohibit it by patent."

This unsatisfactory condition of things led to what is known as the "Statute of Monopolies", passed by Parliament in the year 1623. This was the first patent statute. Prior to this, the whole subject of letters patent had been dealt with by the courts, in accordance with the principles of the unwritten common law of England.

The "Statute of Monopolies" declared invalid all monopolies then existing and relating to the "sole buying, selling, making, working or using of anything within this realm or the Dominion of Wales, as contrary to the laws of this realm," and forbade such monopolies for the future. Certain specific grants were excepted, and there was the further general exception that the statute should not extend to any letters patent then or thereafter granted for the limited terms named, which gave a monopoly of the

> Working or making of any manner of new manufactures within this realm, to the true and first inventor or inventors of such manufactures which others at the time of making such letters patent and grants shall not use, so as also they be not contrary to the law nor mischievous to the State, by raising prices of commodities at home or hurt of trade or generally inconvenient.

During the unsettled periods of Charles I and of Cromwell, there were, as might have been expected, many vicissitudes in the development of the patent law; but the principle that had characterized the English law from the beginning, that a patent might be granted as a reward to the inventor and as an encouragement to others, ultimately prevailed in England, while all the other industrial monopolies of the Tudor and Stuart periods disappeared. Such was the situation of the English law and practice at the time of the American Revolution.

In the colonies on this side of the water, there had, of course, been but little industrial development. In spite of that fact, the value of patents had been recognized and a number had been granted. The first to be issued in this country appears to have been granted by the General Court of Massachusetts Bay Colony in October 1641 to one Samuel Winslow for a process of manufacturing salt. The term of the patent was for 10 years and the grant was conditioned upon works being established within the year. In 1656 the Massachusetts Bay Colony also granted a patent to John Winthrop, son of Governor Winthrop, for the "sole privilege of manufacturing salt after his own particular method" for a term of 20 years. A number of other patents were issued in colonial times by Massachusetts, Connecticut and Pennsylvania.

The articles of confederation adopted by the colonies in July, 1776 contained no provision for the granting of patents, but the states issued patents independently as the colonies had done. For example, in 1785 one John Rumsey obtained patents from the states of Maryland, Virginia, Pennsylvania and New York for a new type of boat which during the previous year had been tried on the Potomac river in the presence of Washington.

Those who framed the constitution of the United States recognized, with characteristic wisdom, the importance of encouraging industrial development. It is interesting to note that a proposition was before the convention that prepared the Constitution, by which Congress would have been empowered "to establish public institutions, rewards and immunities for the promotion of agriculture, commerce and manufactures." This broad but vague provision was not adopted. In its place, we find in the Constitution that authority is given to Congress "to promote the progress of science and the useful arts, by securing for limited terms to authors and inventors the exclusive right to their respective writings and discoveries."

The time has not yet come when we have ceased to admire the far-sighted wisdom of the framers of our Constitution. It is one of the most interesting things in history that it has proved so nearly adequate to meet the radically changed conditions of modern times. Many of our most thoughtful men believe that our prosperity and well-being depend to a great extent upon a strict adherence to the underlying principles upon which it is based. In the hands of a long line of eminent judges who have passed upon it and construed it, it has proved its adaptability to social conditions utterly different from those existing at the time when it was prepared.

Whatever may be its merit as a whole, there can be no question as to the singular completeness and adequacy of the simple clause which I have just quoted and upon which our patent system is based. Acting in harmony with the spirit as well as the letter of the constitutional provision, Congress has adopted a scheme of patent protection the wisdom of which has been shown by the results. No one can say how ineffective the clause might have proved if the clause and the legislation under it had been construed and applied by unwise judges; but the great jurists, from Marshall down, who have developed and fixed the meaning and spirit of other parts of the Constitution, have applied to this section, with the most satisfactory results, the patriotic and far-sighted intelligence that characterized all their work.

It is an interesting circumstance that this provision of our Constitution says nothing as to the promotion of industry or the introduction of new industries. It refers only to the promotion and progress of science and the useful arts. This seems to me to have introduced a radically new idea into the view of the function and scope of a patent system.

The patent system of Great Britain, to which I have briefly referred and which was the only one that had received any development before our own, approached the matter from a different point of view. Its object was to promote progress, primarily by encouraging the establishment of new industries in the Kingdom of Great Britain or the improvement of those already established. The English patent law, from the beginning, was construed as affording to one who brought into England an industry or an improvement from a foreign land, a right to the same protection as that to which he would be entitled if he had been the inventor or the discoverer of that industry or that improvement. The reward of the law was not for inventive achievement. It was for giving to the community knowledge of an art that it did not have before. The man who by reason of facilities for travel or intelligent powers of observation acquired information as to a manufacture long carried on in foreign countries, was exactly on the plane with the man who had originated the idea. This has been a characteristic of many of the important patent systems that have been developed in countries outside of the United States and England. In great part they take the English view. They reward the man who introduces or improves the manufacture and not alone the man who originated the improvement. For the first time in the world, the framers of our constitution laid the entire stress of their effort on the recognition and reward of inventive thought. They adopted the new theory that if men are encouraged to invent by the certainty of reward, or, as Lincoln put it, if the fire of genius is fed with the fuel of interest, the industries will take care of themselves. They believed that there was no way of securing new industries or of making improvements in old industries so effective, as to encourage intellectual effort by way of invention and discovery. As already stated, they ignored the suggestion that there should be other forms of reward for the inventor or discoverer. They authorized only a single reward, a single recognition of his merit, namely, that there should be secured to him the "exclusive right" to his invention for a limited time. It is to be noted that they did not authorize Congress to give him a right that was less than "exclusive"; nor did they authorize any discrimination as to the personality of the inventor or the magnitude and character of the invention.

It is not impossible that the framers of the Constitution fully appreciated the nature and efficacy of the patent system which they were authorizing. If they did, it is only another instance of their far-sighted wisdom and intelligence.

We all know generally the development of this provision of the Constitution under the influence of friendly public opinion, sympathetic legislation, and strong, intelligent, and comprehensive judicial interpretation. We have to-day a patent system which is generally regarded as the best in the world. Under this system, applied science and the useful arts have been promoted as in no other country and at no other period in the world's history.

Much may be said of some assumed abstract quality in the American mind and temperament which has led to our marvelous industrial development of the last century. Many reasons may be given for the existence of the quality that has made this progress possible. It may be referred to climate, to the influence of democratic institutions, to our system of education, to the fact that we as a community are made up of the more enterprising off-shoots of many races which have here met and under our unique conditions have developed new capacities. There may be a certain amount of truth in each or all of these hypotheses. None of them, however, seems adequately to explain the result, nor are any of these considerations so related to some or all of the others as to make it by any means certain that it is for any such reason that we have advanced in industrial achievement by leaps and bounds. During the period of our greatest development, namely, during the last 50 years, we have been closely associated with all the other great nations of the civilized world. They have known of us and of our work. We have known of them and of their work. There has been a constant interchange of ideas, methods and products of manufacture between one country and another. I doubt if any of us, in view of our knowledge of and relations with the English, French, Germans and Italians, can be satisfied that we have done such great things industrially because of our peculiar situation or by reason of any of the special conditions above referred to.

There can be no doubt, however, that we have had a different patent system administered in a different spirit. Is it not reasonable to believe that this is at least the most important advantage we have had in our industrial work and that because of it more than because of any other consideration, we have attained our great success in applied science and the practical arts? I am quite prepared to admit that many other considerations may have played an important part in our development, but it seems to me certain that that development is largely due to the special character of our patent system and its efficiency in encouraging invention.

What is our patent system, not merely as a statute or provision of law, but in its relation to actual affairs? When stripped of all the many refinements that are necessary for its practical application and administration, and when regarded in the simple form in which it is apprehended and appreciated by the millions of people in our community who know of it and are interested in it, our scheme of patent protection amounts simply to the grant to one who has had the intelligence and skill to make an improvement in the useful arts which involves invention, of the exclusive right, for the term of 17 years, to make, use and sell that which he has discovered, invented or designed. Almost everyone in the country knows this much of the characteristics of an American patent. Everyone who has any information on the subject at all, also knows that this absolute right to exclude everyone else from making, using and selling the patented thing for the term of 17 years is one that may be exercised and enjoyed by the patentee exactly as he pleases. He may himself work under the patent. He may sell the entire patent. He may sell a part interest in the patent. He may grant licenses in any form he chooses to any number of people, provided his licenses are consistent with each other. He may give one a right to use only; another a right to manufacture and sell. He may give to one a right, exclusive or non-exclusive, to apply the invention in one field and to another an equally valid right, exclusive or non-exclusive, to apply it in another field. There is no limit to the inventor's absolute control of the thing that he has invented, within the limits of honesty and fair dealing imposed by law generally on all transactions.

Moreover, everyone knows that the cost of taking a patent is ordinarily not great and that once the patent is granted, it remains in force for 17 years without any further expense to the patentee. He is not obliged to work under the patent, nor is he obliged to make any use at all of the invention unless he chooses. The law recognizes that such a requirement is not needed. Self-interest and a desire to get a return from the invention will be quite enough to stimulate the inventor or patentee to effort and to insure commercial development of his invention, if it has any value. At the end of the term, the patented invention is free for all to use.

If capacity for invention can be stimulated at all, there could be no more effective means of exciting it to the utmost than the opportunity of securing just this reward which our patent system gives. Every one of our industrial workers, and a vast number who are not engaged in industrial effort, knows that if one has a new idea in any of the useful arts which amounts to invention, he may monopolize that idea for the term of 17 years. Short as is this period measured by some standards, it seems and is long as compared with the period of the activity of the individual. The inventor may recognize that there is no immediate market for his invention. If, however, he feels that his idea is a good one, he will work it out and patent it with the hope, amounting in most cases to a belief, that during the 17 years of the life of the patent, the art will develop so as to make his idea of value to him. If he is a poor man absolutely unable to go into business on his own account, he feels that if he gets his patent, he has a substantial length of time during which he may seek for help in the commercial introduction of his invention, work up enthusiasm for its exploitation, find a purchaser for it or licensees who will work under it. The manufacturer who is not only concerned with the successful application of his present industrial methods but is looking forward to their improvement, or who is seeking for new things to manufacture, is ready to take hold of new ideas, whether developed in or outside of his own factory, to experiment with them at a large expense and to secure a patent on them, even though he knows that he can not immediately utilize them. He is glad to take the chance that years later the ideas which he thus controls may fit into his industry and become of profit to him for part of the 17 years during which he controls them. The capitalist, large or small, always ready to risk his money in the chance of a substantial return, will take up with a new invention even if he clearly sees that years, during which his disappointments may be great and his expenditures large, are sure to elapse before he can hope to make the fortune which he is after, for he believes that his time for profit will come during the latter years of the 17-year term of the patent. The result is that there is the strongest stimulus to manufacturers, employees and capitalists, and even to those who are not directly in touch with industrial operations, to seek out new ideas, new devices, new methods and new structures and to patent them, because they have the assurance that if the patent is once obtained, the invention will be controlled absolutely for the term of 17 years, during which it may have value, and that if at any time during those 17 years there is a demand for it, it can be handled, as a matter of right, in that way which is most advantageous to the owner. Under these circumstances they are willing to take large chances.

Almost every one knows the uncertainties of patents and patent enterprises. Almost every one appreciates, what is probably the case, that the greater number of patents never prove to be of value. No one may find it profitable to use the invention for which a patent is taken. Many enterprises, based upon patents, fail for one reason or another. But the chances of success, even if they are no more certain than in the case of those who seek for gold in the bowels of the earth, are quite sufficient to justify even the most prosaic man in an enthusiastic effort to promote the useful arts if he has the inventive faculty himself, or to contribute his time or his money to such promotion, as manufacturer, business man, or capitalist, if he comes in contact with an invention that seems to him promising.

As a rule, the systems of foreign patent law are less liberal than ours. The term of the patent is often less than 17 years. It is sometimes more expensive to secure the patent, and not infrequently, after the patent is once obtained, the inventor can not look forward, as he can in this country, to enjoying the right to his monopoly for the term of the patent on exactly the basis he chooses. In some countries he has to face the payment of onerous fees annually or at an interval of a few years, and if such payments are due at a time when he is out of funds or discouraged, as all patentees and patent owners are likely to be even if the invention is one of great merit and sure to be ultimately successful, the patent may be lost for non-payment of the fees. In some countries, the patentee or those interested in the invention have to look forward to the forfeiture of the patent if there is no manufacture under it within a certain limited and often a very short period. It may well be that this period will expire before the art is ready for the invention or before the invention is commercially perfected or before capital can be secured for its development. In some countries the owner of the patent may be forced to grant licenses, the terms of which are fixed without his consent, and be thereby deprived of that control of the invention which is essential to its profitable exploitation.

I believe that if any such provisions had become part of our American patent system there would have been nothing like the same effort on the part of our people to promote the progress of the useful arts as has characterized them from the beginning, and particularly during the last 50 years.

Even as it is, there is discouragement enough to our inventors and patentees. Although our patent system is, in my opinion, the best in the world, the administration of it in the Patent Office and in the courts involves difficulties and annoyances to the patent owner which in some cases seem to him intolerable. For example, no one can be sure that the patent which he gets is valid, nor as to its scope. The Patent Office does admirable work but, of course, sometimes errs, and the entire art can not be known to it. The uncertainty in the application of the law to the facts, which is naturally greater in patent causes than in most branches of the law, makes it a difficult matter to foresee how a patent will be viewed and construed by the courts and leads to more or less conflict in judicial decisions. This is a great evil, affecting not only the owners of patents but the public generally, who are unable to come to a sound conclusion as to their rights even when acting under the advice of competent counsel What will be the finding of the courts on questions of validity and scope can not be foreseen. The methods of taking testimony in patent causes are cumbersome and expensive. It seems certain that an intelligent and well-directed effort on the part of the patent bar and the courts could bring about a reform in this direction.

Such evils characterize the practical operation of all human institutions. We can only hope to minimize them.

It is not at all impossible that the establishment of a single Appellate Court to take the place of the nine independent Courts of Appeal now existing would go a long way towards helping the situation. Such a court would surely bring about harmony of judicial decisions to an extent that does not now exist. It could also criticize intelligently and forcibly the present methods of taking testimony, and stimulate the inferior courts and the bar to deal wisely with this important matter.

The Patent Office can undoubtedly be organized to do more effective work in its examination of applications. On its judicial side in interference controversies, where it has an organized machinery for trying out cases of priority of invention, there is the same cumbersome and expensive procedure that characterizes trials in court, with the added hardship of an excessive number of appeals. This also could and should be reformed.

The difficulties of the American inventor and patent owner, great as they are, and they have been so great as to lead some to express disgust with the entire patent system, are due not to the law but almost altogether to defects, some of which can never be eliminated, in the ancillary machinery of the law; and although inventors, patentees and the owners of patents have in individual cases undoubtedly suffered hardship from the inadequacy of the procedure devised to secure and to maintain the rights vested in them under the constitution, if we look at the matter in a large way there is no doubt whatever that the patent system of the United States has to a notable extent stimulated invention and encouraged and rewarded inventors.

In criticizing the procedure of the courts and of the Patent Office, we must not overlook the inherent difficulties of the situation. The problem is so complex and the administrative machinery has grown up under such conditions, that it is almost wonderful that a more serious situation has not developed. It is to be deplored that there is so much expense, trouble and uncertainty in the administration of the patent system, but it would be much more unfortunate if the law was wrong or if there was, in general, substantial injustice in the grant of patents or the protection of rights and of industries carried on under patents. This I am sure is not the case.

It is easy to find fault with the courts and the Patent Office for apparent or real error in special cases or for ineffective and cumbrous organization and methods of procedure. All human institutions are subject to the same criticism. I am glad, however, to have the opportunity of expressing my own belief, that the Patent Office of the United States, hampered as it has been by inadequate appropriations, insufficient facilities and the pressure of work which has increased faster than the organization necessary to handle that work could be developed, has been, on the whole, more efficient than any other administrative department of our government. Of one thing I am sure, that in no department has there been greater intelligence or greater honesty and sincerity of purpose. Further, I believe that nearly all who are competent to judge, agree with me that the work of the United States courts in patent causes has been of a high order and is entitled to great praise. There has never been a question as to the good intention of those courts and the certainty of their earnest effort to apply and develop, logically and fairly, the constitutional theory upon which our patent system is based. It has not been much of a disadvantage to the patent system or to patentees that the judges have as a rule had no special technical training. Their lack of such training has simply made their work more strenuous. While undoubtedly, as in all other branches of the law, cases relating to letters patent have been wrongly decided, the conclusions of the courts of the United States on patent matters as expressed in the recorded opinions, have been characterized to a marked degree by a sympathy with the spirit of the constitution and the law, and by an intelligent and straightforward application of principles to facts of an unusually difficult and complicated character. The record is most creditable.

But whatever discouragement to invention exists by reason of imperfections in the work of the Patent Office and of the courts, it is a matter of common knowledge that we in this country have the benefit of a patent law which stimulates and encourages invention to a marked degree. The condition of our industries as compared with those in other countries is proof of this, and proof of a higher order than any statistics that are available. What statistics there are, serve only to confirm this view. For example, in 1903, the last year for which I am able to get information as to all the countries, there were issued in the United States 31,046 patents (50,213 applications were filed in that year), while in the three other great industrial countries, England, France and Germany, there were issued in the aggregate 36,110 patents.

It is a familiar proposition that patent protection exists primarily, not for the benefit of the inventor, but for the benefit of the community. It is easy to argue that an inventor should have a property right in his invention, exactly as an author should be allowed to control for his own benefit, his ideas and form of literary expression, which he is under no obligation to give to the public. We all instinctively feel the justice of such a contention. But the right of the inventor as well as of the author, so far as it exists in theory, is of no value to him unless protected by a definite rule of law, and the extent and character of the protection to be granted is to be determined by the community in view of its own interests. If it were the sentiment of the people that an author should have no other protection than the exclusive right to his work prior to publication, and that the right of the inventor should be limited to the monopoly of his invention so long as he could maintain it as a trade secret, the sole ground upon which law or legislation to that effect could be properly criticized would be as to its wisdom or expediency. Exactly as the whole civilized world has come to the conclusion that the author's abstract right should be recognized by securing to him a monopoly of his publications for a limited time under conditions more or less wise and liberal in the different countries, and this not merely or so much with the view of rewarding the author as to encourage authorship, so the patent systems of the world agree in giving legal sanction to property in inventions, partly because of the feeling that the inventor has some abstract right in them, but for the most part as a matter of public policy to stimulate and secure the promotion of the useful arts.

It is not alone by the specific disclosure of particular inventions that the public gains from our patent system. Inasmuch as a United States patent is particularly attractive because of the fact that the expense of getting it is ordinarily not great, and when once obtained there are no further payments to make and no danger of forfeiture for non-working or for any other reason, so that the patentee has the legal right to control his invention and utilize it as he pleases for his own advantage for the term of 17 years, most of the important and significant inventions made anywhere in the civilized world are likely to be patented in this country and thus disclosed to our manufacturers, inventors and technical men soon after they are made. The Official Gazette of the United States Patent Office prints every week the claims of all the patents issued in that week. Copies of each patent may be obtained for 5 cents each. The result is that in every art there are many who read every patent relating directly or indirectly to their work. Thus all new ideas are promptly circulated throughout the community and immediately brought home to those who are capable of apprehending them and working from them.

Every invention is potentially the cause of others. The study of a new idea, whether developed in England, France or Germany, or the United States, when explained in a patent, excites many persons not merely to improve upon the specific form in which that idea is embodied in the patent, but to work out alternative schemes for accomplishing the same result. It is not infrequent that the reading of a patent specification leads to the invention of an important improvement in a radically different direction, because of the train of ideas which arises in the mind of the reader and which might never have been excited except for the disclosure of the patent. Our patent system, therefore, does not merely stimulate invention by promise of reward, but it affords a basis for new ideas by bringing to those who have the inventive faculty just the kind of information and inspiration needed to start them on lines of thought or of investigation that will lead to the promotion of the useful arts.

It is sometimes suggested that our patent system should discriminate against foreigners. The policy of our law from the beginning has been almost without exception directly the other way. I am satisfied that there should be no change in this policy. Not only is our industrial progress stimulated by that immediate knowledge which we get from the patenting in this country of inventions made in foreign countries, as to which we otherwise might not be informed for years, but the issue of such patents gives our industries the benefit of the use of inventions made abroad much earlier than would otherwise be the case.

Sometimes we buy or take licenses under the patents granted to foreigners. Sometimes, although less frequently, the foreigner establishes an industry in this country; but in all cases we get an early knowledge of the foreign work that is of great value as an exciting cause of further invention.

The extent to which, in the aggregate, inventors and those who supply the capital necessary for the development of inventions actually make a profit out of patents in this country is an open question. It may well be that there has been a loss rather than a gain from patents to the individuals who have secured and worked under them. That the community is the gainer from the patent system is altogether clear.

Let us consider for a moment the way in which work is done and applied science and the useful arts are promoted under the stimulus of our patent system.

Those who invent may be divided roughly into classes. The first to which I shall refer comprises the individual inventors to whom once or several times in the course of their lives occurs an idea that seems likely to be of value in the industries. Such an inventor may be of any station in life or of any occupation. The idea may be suggested to him by his work or by accident. If he has faith in it, he develops it, puts it into practical form, either on paper or by actual experiment or construction, and patents it, making in the specification of his patent the full disclosure of it that the law requires. He gets nothing by his patent except the right, for 17 years, to exclude others from making, using or selling his invention except on terms satisfactory to him. Frequently he is without means. Sometimes he has business experience and capacity but often he is utterly incapable of developing or handling a business enterprise. Sometimes he is in such relations to others as to know where capital and business experience are available for promoting the particular invention he has made. Not infrequently, he has not the remotest idea where he can find either. In this matter, a great deal depends upon whether his invention is one definitely germane to an existing art, or radically new or at variance with the prevailing methods and tendencies of the industry to which it is related. Sometimes he is himself without capacity to put his new idea into commercial shape where it will be of value to the community, and he has to secure the help of engineers or inventors of a more practical turn of mind before his invention is embodied in a form which has any real utility.

The value to him and to the community of a patent issued to such an inventor, depends as much on the inventor's skill or good fortune in introducing his invention into actual use as upon the merits of the invention.

It is probable that the vast majority of patents issued are of no real importance. Many of them are for definitely worse contrivances or distinctly more inefficient ways of getting at the result than others already in existence. Many are based upon radically wrong principles, although they seem to involve ideas that are not only practically effective but brilliant in their ingenuity. Frequently an invention is made years before the art is ready for it, and even the most diligent and intelligent efforts can not advance the art to the point where it will utilize the invention. In many, and perhaps in most cases, the commercial success to be obtained in working out any specific patented invention is a gamble only comparable to the gamble of the mining promoter who seeks to develop a new mine from surface indications.

The invention of the telephone was made by an individual inventor whose name will be forever famous in the annals of science and industry. While the result of that invention has been the creation of one of the most far-reaching and important pieces of our modern industrial and social machinery, it is easy for those who are familiar with its early history to see that it might have failed to secure any recognition except as a scientific toy. While the greatest credit is due to Professor Bell for his invention, it is almost equally to his credit that within a comparatively short time after he had solved the problem of the electrical transmission of speech, the wonderful possibilities involved in that invention were definitely foreseen by him at a time when few men had even a glimmering of its real commercial importance. In spite of Professor Bell's clearness of vision, th development of the invention might have been indefinitely postponed, in fact it might never have become such an important part of our social and industrial machinery, if he had not been fortunate enough to find, while his patent was still young, the right capitalists and the right business men to do the work of organizing, developing and financing the industry.

Sometimes these individual inventors find their capacity for originating new ideas so great that they adopt invention as their profession. Of this class of inventors, our fellow-member, Mr. Edison, is perhaps the most conspicuous. It is unnecessary to remind this audience of the wonderful fertility of his inventive genius or the wide range in which he has done marvelous work for the advancement of the useful arts.

Such professional inventors occasionally work with their own capital, and some of them show capacity for embodying their inventions in practical form and the requisite business ability to direct to a greater or less extent the commercial introduction of their inventions. But this is not always the case, and with them as with other classes of inventors, it is generally essential that their inventive faculty should be supplemented by the capital and business energy as well as the technical and inventive skill of others, in order that the joint efforts of all concerned may result in a real improvement in the useful arts.

With them as with the man who makes but one invention, it is only because of the protection afforded by the patent system of the United States, that capital and business experience can be diverted from standard occupations to the chances of an enterprise based upon new inventions. There are too many well-known instances of the absolute failure of what seems a promising invention to make it possible to attract capital and business ability to the inventor's support unless, because of patent protection, there seems to be an opportunity to secure a return commensurate with the risk involved.

The history of the telephone industry also affords an illustration of the activities of another conspicuous class of inventors, whose work under the protection of the patent system of the United States is most effective, and of the conditions under which they make their contributions to the progress of the useful arts.

The business men and capitalists who took hold of the telephone enterprise in the early days, would never have risked their time, energy and money, if they had not believed that by reason of their fundamental patent they could exclude all the people of the United States from making, using or vending telephones without their consent, not for a period too short for effective work, but for one that was reasonably long, namely, 17 years. They undoubtedly foresaw, although very inadequately, that the business upon which they were entering would be full of disappointments; that only by the exercise of the utmost ability and energy could it be made to succeed; that a very great investment would be required; that large sums would have to be spent in engineering and in perfecting apparatus and that they would have to run the risk of judicial decisions as to the validity and scope of their patent. In going on with the enterprise, they took their chances with all these contingencies, hoping and believing that in spite of them, they would secure an adequate profit.

From the very beginning it was clear that the telephone invention in and of itself could be of value only when supplemented by many other inventions which would be found necessary in the effort to make the main invention commercially effective.

Because the business men of the organization knew that suitable apparatus must be developed, and that every added invention would strengthen their position not only during the 17 years of the main patent but during the 17 years' term of each and every one of the patents taken out on subsidiary methods and devices invented during the progress of commercial development, one of the first steps taken was to organize a corps of inventive engineers whose duty it was to make every effort to perfect and improve the telephone system in all directions, first, that it might become of greater commercial value; and, second, that by securing accessory inventions, possession of the field might be retained as far as possible and for as long a time as possible. The result has been a very great number of patents taken by the engineers and inventors of the Bell company for inventions in, or relating to, telephones or telephonic apparatus. Moreover, the patents of others were studied with the utmost care and an innumerable number of outside inventors found a ready market for patents which they secured on their contributions to the telephone art. It is not impossible that nine-tenths of the patents so acquired were for inventions which proved to be of no real importance in the development of the art, but taken all together they have made the mechanism of the business and have given us the wonderful system of telephonic intercommunication that we have to-day. Without the stimulus afforded by the patent laws of the United States, it seems to me certain that the telephone art would not have attained its present situation in the social and industrial organization of to-day, in many times the number of years that have elapsed since Professor Bell's invention.

In the same way, in practically every manufacturing and technical organization in the United States, careful attention is given to the promotion of the particular art, whatever it may be, by the employment of men who have shown the requisite capacity, to make inventions relating to the special industry. Many such inventors are under definite contract to assign their inventions to their employer, receiving compensation for this sort of work either directly or in the form of a salary. If the individual workman in such an establishment who is not under contract makes an invention, it is apt to be acquired as part of a general policy which the employer has adopted and to which the employees have assented, on terms that are agreed upon.

Very many of these inventions make no real impression upon the art and are simply a source of expense and annoyance to the manufacturer. The justification of the manufacturer for the outlay, and the energy devoted to invention in his establishment is found in a general advance in the quality and character of his output and in economies and improvements in operation, the specific value of which can not be estimated, but whose general importance is very great.

I have in mind a particular business enterprise based upon patents which will in a short time, by the introduction of new machinery, have released the labor of not less than 100,000 skilled operatives in this country for other kinds of work than that upon which they were formerly engaged. I knew of the inventions upon which this enterprise is based from the time of their inception. It occurred to an experienced manufacturer, not himself an inventor, that there could be a revolutionary improvement in a certain standard machine. He employed skilled mechanics of inventive capacity to work upon an idea, not in itself involving invention, which he was able to state to them with sufficient clearness. One set of machinery after another was devised, constructed and thrown into the scrap heap. Finally, after the expenditure of more than $300,000, the manufacturer was able to put his first machine into commercial use. More than a million dollars had been invested in the enterprise before there began to be any return. Repeatedly since then very large expenditures have been required to secure further inventions needed to perfect the apparatus. Although the enterprise to-day is a great success, changes are still constantly made in the mechanism, for which changes patents are taken.

If it had not been for the patent system of the United States, the manufacturer would never have even contemplated the development of this machine. If there had been any provision in the statutes by which any patent which he acquired would have been forfeited unless manufacture under it had begun within a relatively short time, as is the law in Germany and elsewhere, he would not have touched the enterprise.

The question is sometimes debated whether or not under the patent system of the United States the inventor himself obtains the share of patent profits to which he is justly entitled. If he does not get his fair proportion of such returns as are due to his invention, the fault is not with the patent system, for the whole matter of dealing with his invention is in his own hands. No one except the true inventor can obtain a valid patent, and he need neither work under it, assign it or any part of it, nor grant licenses under it unless he chooses. In so far as there is any foundation for the contention that under modern conditions, the inventor himself does not get all that he should for his work, the basis for the contention is not the patent system or the law, but the social and industrial conditions which prevail.

It may be argued with equal force and with the same reasonableness or unreasonableness that capital gets more than its share of the return from industrial enterprises as a whole, and without regard to the patent features which are merely incident to them. If wages are lower than they should be under ideal conditions, if salaries of engineers and executive officers are less, it may well be that the inventor fails to get his share, and for the same reasons, which are based solely upon the principles upon which society is organized as the result of an evolution of thousands of years. A discussion of this broad question is outside of the scope of this paper.

No statistics are available on the point, but it is my own impression that there is no valid foundation for the suggestion that inventors are not adequately compensated. It is undoubtedly the case that in individual instances, meritorious inventors fail to secure all to which it might be said that they were fairly entitled as a reward for their work. It is equally true that other things than merit determine to a large extent the reward of the professional man, the artist, the architect and the engineer. It probably would not require very close analysis to show that in very many cases the material reward of the business man and the capitalist is not at all proportionate to his individual merit. Accident, opportunity and particularly the fitness of the particular man for the special environment in which he happens to find himself, have much to do with all forms of reward that come to men whether in the goods of the world or in reputation. This is as true of the inventor as of other men; but taking inventors as a whole, I do not believe that they have cause to complain.

To many of them their inventive capacity is part of their stock in trade. Because they can invent, they receive substantially more by way of salary and standing than would otherwise be the case, as do those who are deft in the use of tools or who show skill as designers or capacity as salesmen. In many instances, some of which have come to my personal attention, the inventor is the only one who has made any profit out of an enterprise based on patents, his associates the capitalist and the business man having suffered great loss. In other instances, both the inventor and his associates have been adequately compensated.

In dealing with this whole question we are apt to overlook the fact that by far the greater number of inventions, particularly at this late stage of the older arts, are mere details of improvement or alternative devices or methods from which, regarded specifically, no large amount of profit can be made by anyone. Such inventions are only valuable as incidents to a manufacture. They can not be segregated and appraised independently.

In spite of occasional cases of hardship such as occur in every business and profession, I believe that the ordinary social and business principles, which, irrespective of the patent law, determine the distribution of the profits of invention between the inventor, the capitalist and the business man, result in securing to the inventor, on the average, as large a portion of that to which he would be entitled under ideal conditions (such as never can be attained) as come to any other workman in our vast industrial army.

In this paper I have not undertaken to deal with the many special features of our patent system which are of great interest, nor to point out to any extent the details in which according to my own opinion the law is defective or capable of improvement. It is quite probable that the amendments to the law which I should advocate would be as unwise and ineffective, in my opinion, as most of those suggested by others. I have only sought to call to your attention some of the underlying principles at the basis of our patent policy and to show how those principles seem to me to work in practice. If I am right in my belief that we have a fair and reasonable patent system which promotes the progress of the useful arts more effectively than any other that has been devised, and that to the beneficent operation of our law is due to a large extent our recognized position of supremacy in the industries, I trust that you will all agree with me that our system of patent protection is entitled to that hearty support and friendly consideration which I believe it to have generally throughout the United States. No human institution or human law is perfect. We all know that there are some provisions in our patent statutes that might perhaps be amended to advantage. We all know that our patent laws like all other laws work hardship in special cases. We all know that sometimes they result in individual instances of injustice, although it is more than probable that there would be a great divergence of opinion as to the particular cases in which there was such injustice. Generally speaking, however, it seems clear that in their present form and with their present spirit as they have been developed and applied by the courts, they are among the most effective agents for the promotion of our national and individual prosperity and as such are entitled to the cordial support of all. They are particularly entitled to recognition as a social and industrial force of the utmost importance by the members of this body, many of whom are inventors of a high order and all of whom are definitely engaged in lines of work which probably could not have been developed to their present state of relative perfection in a thousand years from the date of Faraday's work and the construction of the Gramme machine, if it had not been for the stimulus of the patent systems of the world, and in particular of the patent system of this country.

DISCUSSION ON "THE PATENT SYSTEM IN ITS RELATION TO INDUSTRIAL DEVELOPMENT." NEW YORK, MAY 18, 1909

President Ferguson: The subject chosen for to-night is one in which every member of the American Institute of Electrical Engineers is either directly or indirectly interested. We are especially fortunate in having among our members a man able to discuss this subject so authoritatively. He is a lawyer who stands foremost in his profession, having been general counsel to the largest electrical manufacturing company in this country for more than 20 years. He is able to treat the subject not only from the legal standpoint but from the standpoint of the business man and executive officer, as he was for six years the president of the largest electrical undertaking in this country representing an investment of over 500 millions of dollars, the American Bell Telephone Company.

Francis B. Crocker (by letter): This subject is one in which I am greatly interested. Ever since Charles G. Curtis and I jointly obtained a patent for a telephone call system in 1880, while students at Columbia, I have given much attention to inventions and patents, including the prosecution and defense of patent suits. The paper is particularly valuable because it sets forth the fundamental basis of patent rights, showing them to be well grounded, historically, legally, and morally. They have been recognized for more than 400 years and have had substantially the same legal status in England for nearly 300 years. Their moral justification is found in the fact that they "promote the progress of science and useful arts," in the words of the Constitution of the United States.

It is a common notion, especially among those who have not given the matter much attention, that the patent system is of doubtful benefit; some think it positively obnoxious. This notion probably arises from the fact that a patent being a monopoly, is classed with all other monopolies and shares their unpopularity. The patent right is really a just reward for service rendered to the community; it is also to encourage others to render like services. As stated in the paper, ever since the enactment of the "Statute of Monopolies" in 1623, all monopolies of the objectionable kind, granted for mere "buying, selling, making, working or using" of some already known article are illegal not only in Great Britain but also in the United States, which has adopted fairly closely the legal principles of the mother country. The broad and clear statement of patent rights contained in the paper will do much to put the matter in its true light in the minds of electrical engineers who are particularly affected by patents because of the novelty and rapid progress of their profession.

I agree fully with Mr. Fish that in the main our patent laws are good and that they have been intelligently and honestly administered. Of course mistakes are made, but these arise mostly from failure to understand the extremely difficult technical points. Even when cases have been decided against my interests, I have not doubted the probity of the Patent Office officials or of the federal judges. Considering the extreme complexity of many patent cases, it is indeed surprising that the decisions are generally right or substantially right.

Nevertheless, there are defects, one of the most serious of which is the fact that "the methods of taking testimony in patent causes are cumbersome and expensive," as stated in the paper. Mr. Fish suggests only a very general and far-away remedy when he says: "that an intelligent and well directed effort on the part of the patent bar and the courts could bring about a reform in this direction." While I believe that the better element of the patent bar would be willing to have such reform, nevertheless the volume of business would be reduced, and human nature as a whole could not be expected to put forth strenuous and concerted efforts in that direction. In order to initiate this movement specifically and promptly, I suggest that the Board of Directors be requested to appoint a committee to investigate and report upon what reforms are desirable and how they may best be brought about. On this committee there should be representatives of the patent bar, manufacturers and operating companies (who have to pay the bills), also engineers who do not act as patent experts as well as those who do. This would insure a breadth and balance of views most likely to bring about the best results. The Standards Committee of the Institute has always had a similar all-around representation, and 11 years' experience has proved that excellent work is done by apportioning it to those who understand it best. Under these conditions the various interests are safeguarded and the conclusions are respected.

This same committee could also consider and report upon the establishment of a single United States appellate court in patent cases, as well as reforms in the Patent Office, especially in obtaining prompt and competent examination of applications, simplication of interference and appeal proceedings, etc. The entire revenue of the Patent Office and the past accumulation should certainly be expended to benefit that branch of the public service. There is no reason why the Patent Office should be run at a profit while the Post Office shows an enormous deficit.

Personally I consider the great bulk and complication of expert testimony the worst of all these present evils. Frequently the record consists of many ponderous volumes which could be reduced to one of moderate size and contain just as much or more of the real facts. This bad practice is commonly laid to the dishonesty of expert witnesses. In some cases this charge may be true, nevertheless the bulk and irrelevancy of the testimony would not be much reduced if every expert were perfectly honest. It is *partisanship* which is largely responsible.

Every day we hear arguments on political or social questions which do not affect the disputants to the extent of a single cent, and yet they will wander from the point, fail to admit the other side of the question, however obvious, quibble and struggle to maintain their own proposition even after they are proved to be clearly in the wrong. If on the other hand a question is left to anyone to decide, he will usually consider it in a conscientious, judicial manner and give his best opinion, endeavoring to eliminate obscure or immaterial matter. If two experts were appointed by the court from among specialists of experience and standing, the facts could be brought out in less than one-quarter of the time and space now required to mix them up. Most of the points would be settled with little or no controversy. In case the two experts failed to agree on certain matters a third could be called in; even if his decision were wrong, the case would be so boiled down that the court and counsel could see the precise issue.

The need of this reform is particularly pressing for electrical cases, because judges and lawyers have the greatest difficulty in understanding the electrical technicalities involved. I think that the Institute is the body most interested in and qualified to lead in bringing about the reforms proposed.

Albert G. Davis (by letter): It is difficult to discuss Mr. Fish's paper. The points which he makes seem so self-evident, after he has made them, and the paper is so convincing and so exhaustive, that criticism is impossible. During the last two or three years there has been a tendency on the part of a certain class of inventors and persons interested in inventions to criticise our present patent system. No two of the critics seem to agree on any particular remedy, and many of them violently contradict each other, but they all are in general agreement that something ought to be changed. They seem particularly to be troubled by the idea that the patent situation is being handled by the patent lawyers, and to feel that this is all wrong. The law has been handled by lawyers, that is, by a special class of persons who have given their whole time and attention to the subject, ever since the Babylonians inscribed their judicial decrees and contracts on clay and baked them into bricks. It will probably continue to be so handled as long as engineering is handled by engineers, or as long as the art of healing is handled by physicians.

The patent lawyers of the country, or at least those of them whose standing is such that their views are worthy of consideration, are a unit in their desire to simplify the patent procedure wherever such simplification can be effected without risk of injustice to litigants, and to see that the meritorious inventor receives adequate protection and adequate reward. This desire is only natural, because the minute it ceases to exist, that minute the patent system will begin to decline, and the occupation of the patent lawyers will be gone.

A good lawyer is a man who is trained in the idea of justice. All his instincts are in favor of justice. A good patent lawyer knows the benefit that has accrued to this country from the patent system, and realizes that this benefit is due to our patent system being the best in the world. He knows that bold and far-seeing men, individuals as well as officers of corporations, are engaged in research and development that must cost hundreds of thousands or millions of dollars before any practical results can be brought forth. He knows that this would not be done and could not be done if it were not for the patent system.

The complexity of our present procedure and the delay and expense attendant on any thoroughly contested patent litigation are not the fault of the patent bar, nor are they the fault of the judges, nor, broadly speaking, are they the fault of the system. The truth is that the questions necessarily arising in an ordinary patent infringement suit are exceedingly complex, so that patent litigation is necessarily one of the most difficult and, therefore, one of the most expensive sorts of litigation in which a man can engage.

I think that most competent patent lawyers will agree that most of the discontent comes from patentees or patent owners who have failed to enforce rights because, as a matter of fact, they did not have any rights to enforce; that is to say, people who have not really made meritorious inventions, but merely thought they had. Any patent lawyer of experience will agree with me, I think, that a man who has a meritorious invention and will hold on to it until the art is ready for it, whether that man be a millionaire or a workman at two dollars a day, will receive his reward. He has a piece of property which is of value and which can be sold. He may be foolish enough to allow himself to be swindled out of it, just as he may allow himself to be swindled out of a piece of real-estate, but there are always plenty of manufacturing companies and individuals willing to put money into a meritorious patent if they can only be convinced that it is meritorious.

The present American patent system has been built up by a steady growth and development through a century and a quarter, keeping what is good and rejecting what is bad. As it stands to-day it is the result of the combined wisdom of generation after generation of able lawyers and learned and conscientious judges. It is a better system to-day than it was 50 years ago, and it will be a better system 50 years from now than it is to-day. Like any other product of the human mind it is capable of improvement and it will be improved, but the improvement will not be produced by any one radical change coming at one time, but rather by the same slow growth by which all real legal and other reforms are effected.

Arthur Von Briesen (by letter): [This communication is not original with Mr. Von Briesen; it is a memorial circulated by the Merchants Association of the City of New York.]

Hon. Secretary of State,
The Senators for New York,
The Chairman of the Committee on Patents of the Senate, and the House of Representatives.

This Memorial is respectfully presented to your Honorable Bodies by the undersigned members of the United States Bar largely practising in patent causes. The law recently enacted by the British Government has already injuriously affected the interests of American patentees and manufacturers and calls for action on the part of our Government. Retaliatory measures have been suggested. By Section 41 of the Payne Tariff Act it is proposed to retaliate by subjecting inventors who are not citizens of the United States, when they seek patents in this country, to the same rules and restrictions which prevail in their own countries. But it has been found that such a provision in our law would do violence to International Treaties, particularly the Treaty of 1883, Article 2, which provides that in this country the citizens or subjects of foreign countries who are members of the Treaty shall enjoy the same privileges regarding patents that are enjoyed by our own citizens. Hence the enactment of a law such as Section 41 of the Payne Tariff Bill would constitute a breach of a solemn treaty and it would otherwise create administrative, judicial and commercial difficulties of such magnitude that the provision in question is by us deemed impracticable. In other countries similar restrictions exist which are not found in our law, the result of which is that the citizens of such countries receive much more liberal treatment and greater rights in this country than our citizens do in theirs. We therefore respectfully petition your Honorable Bodies to take measures which will lead to a new International Conference at which the question arising from the enactment of the said law of Great Britain may be thoroughly discussed with the view of bringing about a complete understanding between the nations, and the entire elimination of all needless and harmful restrictions. In such a Convention the representatives of the United States Government should be instructed to lay stress upon the intolerable conditions created by the enactment of the British Law and by the presence of similar restrictions in the laws of other nations. The objectionable nature of such provisions has indeed led to the question whether it might not be best for the United States to withdraw from the International Treaty regarding the protection of industrial property by giving one year's notice as called for by the Treaty. Should we withdraw from such a treaty, we can then be in position to enact retaliatory measures. But why not press upon the representatives of other nations the importance and value of the simple American system, which grants a patentee protection for a certain number of years, without placing any restriction whatsoever upon him, requiring neither the payment of taxes from time to time, nor the enforced manufacture of patented devices, nor the enforced granting of licenses. The American system in its simplicity has worked the greatest benefit upon our people. An inventor very frequently is ahead of his time. When his patent is granted, it may be laughed at, and frequently is, and it has taken some of the most meritorious inventors as much as ten or twelve or even fourteen years after the grant of that patent, before the value of their mental creation became recognized. During all this time the energy of the inventor is at work towards pushing his creation to the front; no discouragement is placed in his path by any restriction created by law, and as a result the industrial development of this country has been greater than that of any other. Where heavy taxes are required to be paid from year to year,—and in many countries taxes increase from year to year,—inventors, unless they are very rich, are enforced to abandon their patents and relinquish that splendid energy which accompanies the unrestricted patentee throughout the life of the patent. It may well be said that thousands of patents which lapsed for non-payment of taxes in foreign countries would have proved of great value, had the inventors been permitted to continue their privileges to the full end of the original term.

Analogous obstacles are created by the laws that require patented devices to be manufactured in the country in which the patent is granted to a foreigner. The intercourse between nations has become so intimate and so thoroughly interlocked that provisions of this nature work more harm than good in stifling, for the imaginary benefit of the home country, the enterprise of intelligent inventors, who bring into play that splendid mental and intellectual competition which, where a patented machine comes from a foreign country and seeks to cover the market, induces the native inventor of higher grade to create organisms of greater importance and greater value than those that come from abroad.

That license restrictions should not be put upon patentees who under the Constitution are to be granted exclusive rights, is a point that has been thoroughly discussed in the case of *Continental Paper Bag Co. v. Eastern Paper Bag Co.*, decided by the Supreme Court of the United States in June, 1908, and reported in 210 U. S. Reports, page 405, where the court after showing the intent of our Constitution and the object of the law to enter into contractual relations with inventors uses the following language;

"The inventor is one who has discovered something of value. It is his absolute property. He may withhold a knowledge of it from the public and he may insist upon all the advantages and benefits which the statute promises to him who discloses to the public his invention." (p. 424); and then says:

"As to the suggestion that competitors were excluded from the use of the new patent, we answer that such exclusion may be said to have been of the very essence of the right conferred by the patent, as it is the privilege of any owner of property to use or not to use it, without question of motive." (p. 429) * * * "In some foreign countries the right granted to an inventor is affected by non-use. This policy, we must assume, Congress has not been ignorant of nor of its effects. It has nevertheless selected another policy. It has continued that policy through many years. We may assume that experience has demonstrated its wisdom and beneficial effect upon the arts and sciences."

> Your petitioners therefore pray that measures be taken towards bringing about at the earliest possible date another International Conference regarding the questions touched upon in this memorial, with the view of bringing the laws of all civilized nations into more thorough uniformity so that no restrictions may be placed in the path of meritorious inventors who are citizens of other countries and who desire to have their inventions duly protected in this country.

Thomas B. Kerr: If the matter of taking testimony were left to me, I would decide it promptly and decisively. I would not permit my opponents to cross-examine my witnesses. That would relieve my clients of their objections. I have read Mr. Fish's paper several times and have got a new view of the patent law from it. I have been at patent law all my life, and have known no other practice. This has subjected me to this kind of criticism: One day I met Mr. Knox, the present Secretary of State at a club in Pittsburgh. We had a patent case together, and I had explained to him that we had to have an expert to testify as to certain scientific matters, and I had come to him for his opinion in regard to certain questions of law, collateral to the specific patent questions involved. He was discussing lawyers generally to some lawyers and laymen. He looked at me and said:

> There is one branch of the profession which should not be admitted to an equal standing with the others. I mean the patent lawyers. If it is a question of mechanics they must hire an expert; if it is a question of law they must hire a lawyer.

I told him that that was the first time I had ever heard defined the status of the patent lawyer and that as I understood society, the most important man to be found was the middle man. The function of the patent lawyer is between the law and science, between the engineers and the court, because the engineers talk in a language that the court does not understand. The patent lawyer must get an inkling of the inventor's meaning, and convey it in simpler language to the court. Judges have confided to me that their greatest difficulty in patent cases was in understanding the testimony of the experts.

I never fully appreciated the Constitution of the United States until I read Mr. Fish's paper. In recent years the only part of the Constitution that I have read more than two or three times, is that upon which the patent system is founded, but I never appreciated the wisdom of that provision until I read Mr. Fish's paper. What possible improvement could be made upon it from a practical standpoint? How can you pay for something with nothing more perfectly than the Constitution pays the price, or prescribes the price which the country shall pay for inventions. It gives to the inventor something the public does not own, and yet it is so perfect a provision that out of it not only does the inventor gain his reward, but the country gains the prosperity which Mr. Fish has spoken about. I agree with him that American progress in commercial, industrial, and scientific lines is largely due to that one provision of the Constitution.

Now what handicap or harm comes out of it? Does it prescribe or put any limiting conditions upon the inventor? Does it in any way dampen his ardor or ability? No! It simply clears the track and says, "Now, run your race." For an invention, properly patented, is but an opportunity given to man, and it is of no value to him unless he puts back of it the same industry, purpose, and judgment which is necessary to success in any other line of endeavor. The fathers who wrote that provision laid the foundation for the most splendid patent system ever devised.

Mr. Fish pleads for support of the patent system. I do too. It has its weaknesses, like every other human institution. But it is the best patent system extant. The engineers especially have an interest in it, because in the future nature, under stress of greater intelligence, boldness, and earnestness of investigation, will yield her secrets much more freely than in the past. There are open to all men the rewards which come to the successful inventor, but the patent system is needed to give him the opportunity to profit by his labor.

Livingston Gifford: I think that the sentiment of the bar is absolutely unanimous in favor of the patent law as it stands to-day. I say, unanimous in a general sense. As Mr. Fish says, every individual has some fault to find, something that he would suggest as an improvement, but everything suggested as an improvement by any individual is generally condemned by almost everybody else. So I think that taking the general sentiment of those who know, the conclusion is that the patent law as it stands is satisfactory.

On the other hand, the consensus of opinion is that the system of administration—the taking of testimony and hearing and deciding cases—is all wrong. It is antiquated and requires some changes to adapt it to present requirements. It has existed for probably three-quarters of a century, ever since the patent law commenced. It is worn out and does not meet present-day demands. It is complicated, cumbersome, and does not reach results. But when all this has been said, how is it to be made any better? We have practiced under it for over one-half a century, and everbody is condemning it all the time. Yet I have never heard a suggestion from anyone of any improvement that anybody else would agree to as being an improvement. As soon as an attempt is made to curtail the system, one runs into difficulties just as great in other directions.

It is very easy, and the common practice of everybody under all circumstances, to say, "have a committee appointed". But Mr. Crocker does not suggest any change for a committee to consider. It would be useless to appoint a committee and expect them to revise a system which has existed for three-quarters of a century, without suggesting in advance any scheme of improvement.

It seems to me the proper thing is to follow the suggestion of Mr. Fish; that is, to have a court to take and hear all patent cases as a court of last resort, so that the court can become acquainted with all of the difficulties that arise. That court, perhaps coöperating with all interest in patents, may work out a solution of the problem and cure the evil in the long run. I see no other possible way of accomplishing it.

E. W. Rice, Jr.: Mr. Fish speaks of the work of the inventor as that controlling the forces of nature and teaching man how to apply those forces to shaping and transforming the raw materials which are available for his use, as distinguished from intellectual, moral, social, and imaginative development.

I have no doubt Mr. Fish will agree with me that one of the chief characteristics of the inventor is his imaginative quality: I do not think a man can invent anything of value who has not the imaginative quality developed in very definite manner.

Mr. Fish's statement

> It has not been much of a disadvantage to the patent system or to patentees that the judges have, as a rule, had no special technical training.

is of great interest to me, for at one time, I thought it was a very great disadvantage not to have had this training. I still think it would be desirable in an appellate court, such as Mr. Fish has suggested, for one of the members to have a first class engineering training. Nevertheless, my experience with lawyers and patent lawyers has astonished me. They show such wonderful capacity in grasping abstruse engineering problems, and in restating them in such a clear and simple manner that the so-called expert is often confused. I think, therefore, that even without an engineering expert sitting as a member of the court, the system is fairly safe. That has often happened in my experience.

It is self-evident that one of the great advantages of our patent system is the stimulation of invention. Mr. Fish has referred to the rewards of inventors. It is a most difficult subject, one with which I have had to deal personally, and on many occasions I think we would all like to see inventors reap the richest rewards of their efforts. However, I believe that inventors, as a class, do receive a full measure of reward, compared with similar efforts in other lines. It happens under our patent system that a monopoly is given only for a certain kind of ideas. Now there are other ideas and efforts just as important and valuable which are not patentable. The manager of a works or the executive of a business must use great originality and great skill in managing the business, but he has no means of obtaining a monopoly on his ideas or methods.

It is also true in many cases that inventions, as Mr. Fish states are only valuable as incidents to the manufacture, and cannot be segregated and appraised separately. It often happens that an inventor makes an invention which he believes will save his employer a large sum of money, and he feels that he ought to be rewarded accordingly. But the difficulty has been accurately to determine the saving in the particular case. Others have contributed to make that invention possible, and others must help to make it profitable; and it is impossible to segregate and value the individual contribution.

As to the improvements of the patent system, I think it would be difficult to offer any suggestion beyond the one Mr. Fish has made as to a single court. We all agree, I think, that it would be a great improvement if some method could be devised to limit cross-examination. I have felt very keenly at times that my time has been wasted by opposing counsel. I think all engineers and inventors brought into patent cases, who are not patent experts, regard the waste of time given to the taking of direct and indirect testimony, as something almost unbearable. They would rather be engaged in the work of designing or inventing new apparatus. Therefore, any suggestion which will improve the practice in that respect will be welcomed.

Chas. P. Steinmetz: After the very comprehensive paper of Mr. F. P. Fish, I cannot see how I can add anything, still less criticize the paper; but shall merely discuss one particular feature of the patent situation from my point of view as an inventor. I have made a few inventions myself. The direct financial gain which I have received from inventions amounts to $500. Indirectly, in salary and reputation, however, I believe I have received at least the value of my inventions; so that I can find no fault in my personal experience, and my treatment as an inventor. Still, I recognize that considerable fault is found with the operation of the patent laws by inventors and others.

In criticizing the operation of our patent laws, I believe it very important to realize the point of view from which the criticism is made; because what may appear as severe criticism from the manufacturer's point of view, may be desirable and necessary from the inventor's point of view; and inversely.

To illustrate: The requirement that the invention should be manufactured within a short time limit of one year or two years would offer very little handicap to the manufacturer who can arrange to have somebody put to work on it; but it would be fatal to the inventor, as it would practically deprive him of the chances of reward, since most inventors are not able to carry out the manufacture of their inventions on their own capital. Therefore, if this were a legal requirement, the inventor would have to turn over his invention to a manufacturer at any price, or lose it altogether. So, you see, we may criticize from one point of view a feature which is entirely justified from another point of view; for you can realize that the manufacturer may desire to have such a clause, as it would turn the inventor over to him, helpless, while the inventor should for the same reason strongly oppose it.

I propose to discuss this paper from the standpoint of the inventor, and not that of the manufacturer or the capitalist; because I believe the inventor who has created something which did not exist is the one to be rewarded, and to reap the benefit, while the capitalist, who makes the exploitation of the invention possible, by financing the business, or the manufacturer, are entitled to interest on their investment, to the return of the money they put out, and an additional return appropriate to the risk of the investment.

Developing an invention is not a safe investment like putting money into real estate, but is rather a gamble; and, therefore, the returns of capital should be very much higher to compensate for the risk involved. We do not realize the risk of investment in an invention because it is human nature only to see success, and forget failure. For instance, we consider the success of the Bell telephone, but we forget the Keeley motor. At the present time, everybody knows that the Bell telephone was a great invention, and the Keeley motor a humbug, yet in the view of the technical adviser, at the outset both appeared as wild fancies and capital could in neither case get reliable technical advice. So we must consider the time when capital was approached, and not the viewpoint of the historian whose judgment is guided by experience. Five years ago certain inventions in aeronautical matters would have been ridiculed. Nobody would dare to do that to-day, after the recent success in that field.

My opinion is that the patent laws should be drawn and executed in such matter as to give the greatest benefit and reward to the inventor. The ways of exploiting an invention by an inventor are three-fold. 1. The inventor may proceed to develop the invention for commercial use with his own capital; 2. He may interest capital in his invention; in short form an exploitation company. 3. The inventor may turn over the exploitation and development of his invention to an existing manufacturing company engaged in similar work.

As to the first point, the development and exploitation of the invention by the inventor: at present, in the field of electrical engineering, the cost of development up to commercial exploitation of most inventions is so high, as to be far beyond the means of most inventors; and therefore, this is not feasible. Furthermore, the inventor is frequently not a good designer, and usually an inferior business man and administrator; therefore the chances are against his handling his own business satisfactorily. Besides, this method is not economical, as it deflects the time of the inventor from further creative work. Therefore, this method is feasible only in such rare instances, that it hardly needs to be considered. The second method: to interest capital in the development of the invention, the invention must represent a tangible value; it is the market value of the commodity on which depends the attraction to capital. This depends on how far the invention can control the industry or part of the industry to which it is related, and how safe the control is; that is, how good the chances are that the patent may be sustained finally by the court. Even with this assured, it still is an uncertain value, because it may never develop, but unforeseen difficulties may kill it, or just as it begins to develop and become profitable, somebody may invent something similar to it, which the courts consider as non-infringing. Or, again, when the commercial exploitation is ready, some other inventor may do the same thing, in a simpler and better manner and destroy the former invention just when it was about to start on a paying basis. The inventor needs the capital to develop his invention. The capitalist does not need the inventor. The stronger of the two parties is the capitalist; and therefore the control must lie with the capitalist and not with the inventor. It is not a question of morals, but the result of an economic condition, which in this case operates against the inventor. Very much more favorable is the situation of the inventor with regard to an established manufacturing company in similar lines, because in this direction the inventor has more the upper hand. He can hold back the invention until it is needed by the manufacturer, and the manufacturer has to come to terms, or as is more commonly the case, until the manufacturer realizes that this invention offers a certain financial advantage in his field, and therefore is willing to share the advantage with the inventor. As in this case, the conditions are more favorable to the inventor, it is the usual method of exploiting an invention.

The value of an invention, that is the reward which the inventor can expect, depends on its market value as a commodity. The market value depends on the control which the invention offers to the industry or branch of an industry, and the certainty of this control. That is, it depends on the broadness of the patent covering the invention, and the probability or certainty of the courts sustaining this patent. This is the feature which the inventor very often does not realize. He may in some individual cases be handicapped by broad inventions of others, from exploiting his detailed invention, and be led to the idea that broad patents are objectionable. But he does not realize that any limitation of the patent is an advantage to the exploiter of the invention, but not to the inventor. For instance, an engineer may get the conception, and make the invention that by combining several alternating currents, acting in different directions at different times, he can get rotation; and thereby transmit power. The patent of such a conception may be broadly covering the production and transmission of power by the combined action of several alternating currents, displaced in phase and position, or it may be limited to the construction of the particular motor, having two sets of field poles energized by two alternating currents displaced in phase. In the broader case, it would cover the use of two- or three-phase, secondary short-circuited member or energized by direct current, separate polyphase currents or currents derived by splitting the phase of a single current, or many other combinations which the inventor did not and could not think of, because the one who conceived the general idea, cannot think of all the particular applications to which it can be put. Such a broad patent would have a value assuring the inventor an adequate compensation for his broad idea. If, however, the patent is limited to a specific application which the inventor carried out, it makes the patent worthless, and deprives the inventor, who had the broad and fundamental conception, of the value of his work, because the first conception must necessarily be the crudest, the least refined, and least efficient, and any further development or modification thereof, after the general method has been shown, would, naturally, usually constitute a better way of doing it; and if the inventor is barred from the control of these lesser improvements, the fruit of his work and the results would accrue to those who had improved in detail on his particular principle. That would not be fair, and would be very harmful to the value of an invention, because it would make it possible for the benefit of a fundamental invention to be reaped by someone who had simply made a modification or shown another way of doing it, of which the original inventor did not happen to think.

That is why I say the broadness of the invention is one of the most essential things from the point of view of the benefit of the inventor. Not so much from the point of view of the manufacturer, however, for the manufacturer may find it more convenient to limit it, for then he would not have to come to terms with the inventor of the fundamental idea. So the advantages are different from different points of view.

When the invention is finally adjudged by the court, the ownership of the invention has usually left the original inventor, and we are very liable then to imagine that it is of no moment to the inventor, as he has no further financial gain in the question of whether the invention is sustained or destroyed by the court. We do not realize that the destruction of a patent by the courts reduces the market value of all other inventions just as much, and any patent broadly sustained increases the market value of all inventions, and it is of special advantage to the inventor to have the value sustained, even though there is no direct financial gain from that particular patent. The failure to maintain a patent in court means the destruction or depreciation in value of all inventions, and that is the most serious blow to the inventor. To the large manufacturer in the industrial field it is rather immaterial. The destruction of fundamental patents, may destroy his monopoly of certain fields, but at the same time it would relieve him of the necessity of buying the control of an invention, and thus it would merely mean for the large manufacturer a readjustment of business methods, but would be neither a gain nor a loss. Many branches of business are monopolistic without being protected by a patent. Many are held as a monopoly where the patents expired years ago, and still the production of that commodity is carried out almost exclusively by the same manufacturers as before. Business methods, and not patent rights, give their control. To the inventor the destruction of a patent can only be a disadvantage. This is one of the most dangerous features. It is fortunate that the courts in general have been rather inclined to sustain patents. There is a great handicap in that direction, however, because electrical engineering has progressed enormously, so that what was a great invention ten years ago, is so self-evident to-day, that we do not realize how much of an invention it once was. One of the greatest difficulties after the lapse of many years is to imagine one's self back to the time when inventions were made; when what was a great invention has become common knowledge to every schoolboy, and we find the invention expressed in the terminology of the bygone days, when it commonly was impossible to describe ideas in the exact terms of to-day, as these terms did not yet exist in the language.

That is what you engineers and inventors must guard against. It is to our advantage, and nobody else's, to have the patent law allow us to make the claims of every invention sufficiently broad to cover all modifications of our fundamental idea which may be made, and to have the patents broadly sustained by the courts, because these two features constitute the market value of our work, and we are the only ones benefiting by it.

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CENTRALIZATION OF POWER SUPPLY

President's Address

BY LOUIS A. FERGUSON

The most prominent characteristic of present-day industrial development is the tendency to consolidate. It is so apparent on every hand that this may well be called the Age of Centralization. The economies that may be effected by large production and centralized direction are being appreciated more and more, and extremely large industries have been, and are being, built up by combining many individual plants. In the main, such combinations have resulted in material benefits to the country and its people.

The lessened cost of wholesale manufacture permits a lower selling price, thus placing the commodity within easier reach of a larger number. The greater economy of production resulting from manufacture in large quantities and with improved methods is and will continue increasingly to be a material factor in that very important problem of the conservation of resources, which is so prominently before this and other countries at the present time.

In the industry of electric power production the advantages of centralization seem thus far to have failed somewhat of full appreciation, but the awakening is apparently at hand. In a few noteworthy instances centralization was planned and put into effect some years ago, and the work already done will blaze the way for others. When the economies of concentrated management and large production are more generally understood the growth of centralization will be rapid.

From whatever standpoint we view the problem the advantages stand out boldly. The investor will be more favorably impressed with large issues of securities which require no detailed information. These securities will be easily marketed and on much more favorable terms than is possible with the smaller issues of individual companies. Large as this saving is, by far the most important one results from the economies effected by combined investment and output. The load-factor of our central stations; that is, the ratio of the average load to the maximum load, absolutely controls the earning capacity of the investment. The cost of generating and distributing electricity consists primarily of fixed charges on the investment and of operating costs. The fixed charges are independent of the hours use of the equipment; therefore, if the load continues heavy for long hours daily the fixed charges are distributed over a larger output and the cost per unit of output is thereby lessened. In other words, with long hours' use a greater output follows, and greater earnings are produced without any increase in the investment. Obviously, therefore, the greater the proportion the fixed charges bear to the total cost the greater will be the effect of the load-factor. In modern large power systems, as in water-power plants, the operating costs are now so low that they represent a comparatively small part of the total costs, the fixed charges constituting by far the larger part. The importance of a good load-factor is thus apparent and everything that will improve this factor should be sought.

The yearly load-factor for any one class of service is determined largely by the seasons, the habits of the people, and similar conditions which ordinarily do not change. Improvement in load-factor must therefore be obtained largely by combining different classes of service, the maximum demands of which occur at different times of the day or of the year. Also, the larger the number of customers in any class the better will be the load-factor.

The ratio between the sum of the maximum demands of various classes of service to the actual simultaneous maximum demand is termed the diversity-factor, and the more non-coincident peak service that is combined in one system the greater will be this factor. It is here that centralization presents its most marked effect in increasing the load-factor and thereby the economy of production. The addition to a central station system of business having a high load-factor, such as power business for all-the-year-round service, amusement parks, auto charging, and refrigeration for the summer, utilizing the otherwise idle investment, is desirable not only in itself but also because it reduces the cost of the entire output.

The whole community through this reduction in cost is thus benefited by centralization, since the central station company is enabled to sell its product at a lower price to the small consumer because of the improved condition of manufacture effected through the supply of its product to the large consumer.

In the power station the larger output of combined loads will permit the use of large generating units which have a high performance efficiency, and which require a comparatively small operating force. This results in further reduction of costs. The investment per kilowatt, not only for the apparatus but for the land and building as well, is also less for large units, and the total reserve required by the centralized system will be but a small fraction of the combined reserve required where the load is furnished from individual systems. The saving in investment in this single item of reserve alone is an important factor in the problem. One of the leading causes for the success which has attended the development of the electrical industry in this country has been the standardization of equipment, and the American Institute of Electrical Engineers has been the active leader in this important work. It is still a far cry to the ideal but all steps taken should be in the forward direction.

Centralization leads toward standardization. In the present state of the art, generation will be by three-phase alternating current and the predominating demand will determine the frequency, be it 25 or 60 cycles or some other frequency. If, however, the demand in any community for an auxiliary standard frequency becomes sufficiently large, even though it remain a small part of the total output, then generation at this auxiliary frequency is justified; but connecting links of ample capacity should be provided between the sets of generators of different frequency so that the advantages of the diversity-factor and of common reserve may still obtain. The voltage should also be so chosen that the transmission cable may be interchangeable between the two systems.

An incidental advantage of centralization which, however, is of great sociologic importance in a community, is the resultant cleanliness due to the absence of countless smoking chimneys. This fact is being actively recognized by civic improvement bodies, and such recognition is a valuable asset to a central station company in the prosecution of its industrial power campaign.

One of the early and prominent examples of centralization is found in England where the Newcastle-upon-Tyne Electric

Supply Company furnishes energy to one of the most important manufacturing areas in the United Kingdom. A special effort has here been made to develop particularly the industrial power business, and the general adoption of electricity has had a marked effect on the industrial conditions in that district. The tramways are operated from this system as well as electrified steam roads. In many of the smelting mills the waste gases are used to produce steam in boilers and the energy thus derived is used in turbine stations and is fed into the general system, the same smelting mills being in turn customers of the supply company. The total load is not so very large compared with that in some of our American cities, but this system is mentioned in such detail because it typifies what can be done in the way of centralization. There is still a good deal of independently produced power in the district, but it will undoubtedly eventually be won over by the supply company. Even though the difference in efficiency between the smaller turbine units and the larger units is decreasing, the diversity-factor will in most cases enable the supply company to underbid independent producers.

The diversity-factor is the very foundation rock of centralized energy supply. It is the birthright of the central station; the fundamental reason for its existence; and its resultant value belongs to the central station company.

In some American cities, as already stated, the total load is considerably greater than in the example just cited, but the centralization possibilities are only just beginning to be developed.

The system of the Pacific Gas & Electric Company with its hundreds of miles of transmission lines, its many customers among the mines dotting the hills, and the many cities receiving electrical power from the company, is perhaps the nearest approach to the Newcastle system. At Niagara the transmission lines are reaching out in all directions, and we may hope to see one of the great industrial centers of the future in that locality. At the present time there are many independent companies, and the full benefits of centralization will not be realized until the stations are loaded up to the point where they will be compelled to arrange for interchange of energy.

Chicago, because of its strategical location regarding transportation, is certain to remain one of the world's greatest markets and industrial centers. If the imagination were allowed full play the possibilities in power requirements of the future in the Chicago districts would appear almost boundless. A vigorous start toward centralization of power production has already been made. Street-railway power houses have been shut down and the energy for the operation of the street railways is purchased in whole or in part from the central station company.

The supply of power for electrified steam railways is one of the possibilities of the near future, and engineering plans and expenditures of past years have been made with a view of taking care of wholesale industrial business on a comprehensive scale.

In a large number of cities two prominent public services—street railways and electric lighting—were originally inaugurated by one company, and with the natural growth and development of the two systems the electrical generation has in many cases been unified so that one set of generators furnishes energy for both railway and lighting. However, in most of these cities the industrial power business has not been vigorously developed, either because of lack of appreciation of its value or timidity on the part of the supply company in making sufficiently low prices to obtain the business.

There are also very few, if any, communities or territories in which the centralization of power supply for all purposes has been effected and in which electric power is utilized in such manner that the best economic results are realized. By combining all systems of neighboring cities within a radius of 30 or 40 miles into a single centralized system, a great saving in production would result and in most cases an improvement in service as well. The utilization of water-powers will help in this direction.

The monopolistic character of the electric power industry is now being recognized by the intelligent public, and monopoly privileges with proper regulation are being granted as the best safeguard for the interests of the people. The legal way is thus being paved for the beginning of centralization. Such centralization will naturally include the power for electrified steam railways, the universal coming of which is but a matter of time. In most instances the total amount of power required by a railroad for its terminal and suburban service, even where counted in the tens of thousands of kilowatts, is but a small part of the total power required for all purposes within the same area.

If this railway power were generated in a separate plant the load-factor would be far below that of the central station and the necessary reserve capacity would require a high fixed charge to be carried by the plant. With less reserve the reliability of the service might suffer disastrously. No railroad could thus generate its own power as cheaply or as securely as it may be purchased from a properly directed central station company. This applies also and to an even greater extent to power production for industrial uses or to individual generation for any purpose.

In cities where the power production is not centralized, a multiplicity of systems of voltages and often of frequencies is usually found, and the duplication which spells waste is abundant Without the economies resulting from centralization, the price of the output will necessarily remain higher than otherwise and the community must pay the cost. With the lower efficiency of generation the fuel resources are wasted and the entire country will ultimately suffer as a result. It has seemed to me that a condition of such transcendent importance to the electrical profession should receive liberal attention and consideration from our Institute. We, as an organization, have a large part to play in the development of the art of electrical application as well as in electrical science. There is scarcely any branch of the electrical industry which does not ultimately affect or which is not in a measure affected by this development.

The progressive work of the electrical engineer will determine with what success we can reach out into these larger fields. The mechanical engineer has given us a steam turbine of greatly improved economy; it is for us to improve still more the method of transmission and conversion and the application of electricity in the arts. High-voltage transmission made possible our entry into this field, but, while very great advances have been made, there are still some unsolved problems in this field, particularly with regard to underground transmission. There are also many problems and countless opportunities in connection with the utilization of electrical energy. The successful solution of these problems is of the utmost importance.

It is for the commercial electrical engineer (which really includes nearly all of us) to educate the layman and particularly the power user to an appreciation of the superiority and desirability of electric service and to emphasize the material and ethical advantages to a community of centralized power production. It is for the technical electrical engineer to furnish him with the sinews of war, with the ammunition to conquer in the fields where waste, where useless dissipation of energy prevails. We should bend every effort to advance the cause of centralization with its resultant economic gains. Those connected with the manufacturing interests especially should not tolerate for an instant a selfish backward step within their fold.

As we meet here in convention to gain a broader knowledge and to discuss important problems let us think of these opportunities which our profession affords in this grand movement for world betterment, this guiding of the forces so that Nature's bounty to man will bring to him the highest and greatest good. The thought carries with it inspiration and enthusiasm and a determination to do our part, individually and collectively, in the successful upbuilding of an industry which means so much to the economic development of the country's resources. Some day, in the centuries yet unborn, the broadening perspective of time will show more clearly the full significance of these days' accomplishments. Surely, gentlemen, nothing could be more inspiring to greater effort than the knowledge that we have in our hands the means for this achievement.

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THE CONVECTION OF HEAT FROM SMALL COPPER WIRES

BY A. E. KENNELLY, C. A. WRIGHT AND J. S. VAN BYLEVELT

It is well known that when an electrically heated wire is supported in air, it dissipates its heat by conduction, radiation, and convection.

Conduction takes place longitudinally through and into the metallic terminals of the wire, and would take place laterally through the air, if the latter were kept at rest like a rigid medium. The metallic conduction at the ends may be eliminated by confining observation to parts of the wire not near the ends. The lateral conduction through the air is also negligible, because the air does not remain at rest but expands and flows convectively. Consequently we may safely ignore conductive thermal loss.

Radiation loss from the wire is a function of the surface area of the wire, its temperature, the nature of its physical surface, and the temperature of surrounding substances. For a given wire with a given surface condition and in a given environment, radiation loss is regarded as a function of temperature only.

Convection loss from the wire is a hydrodynamic phenomenon, involving the flow of air past the surface of the wire, and the amount of heat which this moving stream of air can carry off. Very little seems to be known quantitatively about convection. It is the object of this paper to describe a research made on the convective loss of heat from small copper wires, of less than 0.7 mm. or 27.5 mils diameter, and to present some quantitative results arrived at from the observations.

In order to study convection loss to advantage, it is desirable to experiment on small wires; because, for a given temperature elevation of the wire, the radiation increases in proportion to the surface area; whereas the free convection is independent of the surface area, to a first approximation. Consequently, a wire of small surface area per unit of length, *i.e.*, a thin wire, will have relatively small radiation loss by comparison with its convective loss. On the other hand, when radiation loss is the subject of investigation, it is desirable to employ conductors of large surface per unit of length.

We may divide convection into two classes:

1. Free convection, when the wire is supported in free still air; that is, air substantially free from draughts, or movements except such as may be produced by the heated wire alone.

2. Forced convection, when the wire is in motion relatively to the surrounding air; that is, when the wire is either moved bodily through the air, or is held in a stream of moving air.

An electrically heated wire is therefore subject to free convection when it is supported at rest in still air, substantially free from draughts or wind motion. It is subject to forced convection when it is either moved bodily through the air, or when it is placed in a wind.

In order to separate convection loss from radiation loss, it is desirable to operate the wire under test at constant temperature and at a constant temperature elevation above surrounding solid bodies. The radiation loss will then be constant, and changes in the surrounding air will give rise to changes in heat dissipation that may safely be attributed to changes in convection alone.

The experimental methods employed in this research were:

1. To vary the atmospheric pressure surrounding the test wire, under conditions of free convection, and to measure the change of electric power required to maintain the wire at constant temperature elevation.

2. To subject a wire to varying wind velocity, under conditions of forced convection, and to measure the change of electric power required to maintain the wire at constant temperature elevation.

FREE CONVECTION AT VARYING ATMOSPHERIC PRESSURE

General plan. A short length of the copper wire under test was supported horizontally* in an air-tight tank and supplied with a steady current from a storage battery. By adjusting the current strength, the wire was kept at constant resistance, and, therefore, at constant temperature. The pressure of air in the tank was varied by means of an air-pump.

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* It has been found that, other things being the same, a wire supported in a vertical position becomes slightly hotter than when supported horizontally, apparently owing to the action of the enveloping stream of convectively heated air.

Copper wires. Three sizes of small, bare, soft commercial copper wire were employed, the particulars of which appear in the following table.

Electrical connections in free convection tests. The connections employed are illustrated in Fig. 1. A storage battery E, of from 4 to 16 volts, supplied current to the main circuit R^1, R, A, h. The resistance h was an adjustable carbon rheostat. The current strength was measured on a standard laboratory ammeter A, the scale of which had recently been calibrated. The resistance R is that of the length of the test wire supported horizontally inside the pressure tank $B\,C\,D\,F$. The constant resistance R^1 was of German-silver wire, selected as approximately equal to the resistance of the test wire R. Pressure wires were taken both from the constant resistance R^1 and the test wire R to the coils G^1 G of a differential galvanometer. If G and G^1 are the respective resistances of the galvanometer coils, we have at any differential balance:

TABLE I

PARTICULARS OF COPPER WIRES USED IN FREE CONVECTION TESTS

Test-wire No.	Diameter		Cross-sectional area sq. cm.	Surface per linear cm. sq. cm.	Length of wire under test cm.	Resistance of wire @20° cent. absohms	Resistance of wire @ 0° cent. absohms	Linear resistance @ 0° cent abs-ohms/cm.	Resistivity @ 0° cent. abs-ohm-cm.
	Cm.	Inches							
1	0.01143	0.0045	1.026×10^{-4}	0.03591	30.88	0.5133×10^{9}	0.4736×10^{9}	153.4×10^{5}	1574
2	0.02616	0.0103	5.374 "	0.08219	118.6	0.3784 "	0.3491 "	29.44 "	1582
3	0.06907	0.0272	37.47 "	0.217	102.5	0.0467 "	0.04308 "	4.203 "	1575

$$\frac{R}{R^1} = \frac{G+\rho}{G^1} \qquad \text{numeric} \quad (1)$$

where ρ is an adjustable resistance capable of being inserted in either galvanometer circuit.

Method of measuring. The resistance of the test wire having been determined carefully with a feeble measuring current, a temperature elevation was determined on for the test wire. To this temperature elevation corresponded a test-wire resistance:

$$R_T = R_0\,(1 + 0.0042\,T) \qquad \text{absohms† or c.g.s. mag. units of resistance.} \qquad (2)$$

Where R_T is the resistance of the test wire at the working temperature T degrees cent., R_0 its resistance at 0 degrees cent., and 0.0042 the assumed temperature coefficient of resistivity for copper* used throughout this research. If the temperature of the air in the tank was t degrees cent., the temperature elevation of the test-wire was $\theta = (T - t)$ degrees cent. The correct value of ρ in Fig. 1 was taken from equation (1), to give differential balance at R_T; so that as long as the galvanometer indicated that balance was maintained, it was evident that the temperature elevation $T - t = \theta$, of the test-wire, was constant. The current strength in the main circuit $E\,R^1\,R\,A\,h$ was then kept at such a value, by adjustment of h, that the differential balance was maintained. This current strength was measured on the ammeter A, as the air-pressure in the tank was changed. The apparatus used is illustrated in Fig. 12, from a photograph.

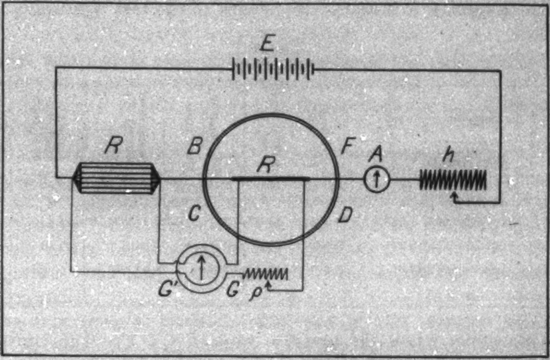

FIG. 1.—Electrical connections in measurements of free convection.

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† An absohm is the c.g.s. magnetic circuit of resistance. See TRANSACTIONS, A.I.E.E., Vol. XXII, p. 534.

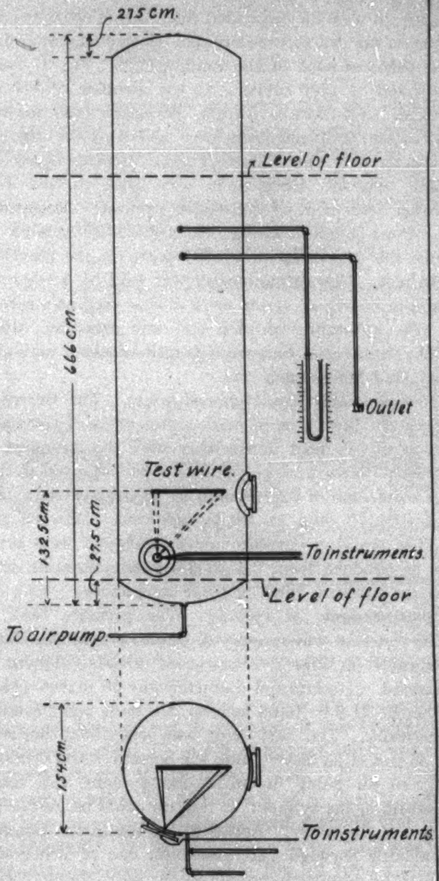
* Standardization Rules of the Am. Inst. of El. Engrs: Third Edition, 1908, p. 32, Sec. 360.

The galvanometer. The galvanometer used was of the Edelmann type, in which a suspended ring magnet swings in a copper cylinder, so as to secure suitable electromagnetic damping. The resistance of each of the windings *G G′*, Fig. 1, was in the neighborhood of 1800 ohms. At the distance of 140 cm. between scale and mirror, 1 mm. deflection was produced by approximately 0.14 microampere. The periodic time of the galvanometer was about five seconds. The damping ratio of successive opposite elongations was 2.55; or the Naperian logarithmic decrement of successive opposite elongations was 0.9361. Four complete swings, executed in 20 seconds, sufficed to reduce the deflection to 1/1790 part, or, for practical purposes, to rest. The galvanometer was read by a telescope and scale, and in nearly all of the work it was used as a zero instrument. The resistance of each coil was measured after each test. The differential balance was also checked, and, if necessary, adjusted before each test.

The German-silver constant resistances. The German-silver resistances *R′*, Fig. 1, were made up of grids of German-silver wire, so as not to heat appreciably with the strongest testing current used. Two such resistances were employed in different series of tests, one of 0.4248 ohm at 18 degrees cent., and the other of 0.04572 ohm at 18 degrees cent., between pressure wires. The working current values employed were ordinarily such as to produce from 0.4 to 2.0 volts potential difference between the pressure wires of these resistances.

The pressure-tank, or cylinder. The pressure tank, inside which the test wire was supported, was a vertical cylinder of the form indicated in Fig. 2, constructed of ½-in. (1¼ cm.) steel plates riveted. Its internal diameter was 60 inches (152 cm.) and its height 21.8 ft. (6.66 meters), the ends being rounded off hemispherically. The test wire was supported horizontally, about 4.36 feet (1.33 meter) from the bottom of the cylinder. A steam-driven air pump, in an adjoining room, was connected to the bottom of the cylinder, so that air could be pumped either into or out of the latter. Access to the interior of the cylinder was obtainable through two manholes, one of which enabled the wires to be admitted through an air-tight gland.

The atmospheric pressure in the cylinder was measured by means of a glass U-tube manometer containing distilled mercury, one leg of this tube being connected to the cylinder and the other left open to the outside air. The pressure in the tank at any time



275 cm.
Level of floor
666 cm
Outlet
Test wire.
132.5cm
27.5 cm
To instruments
Level of floor
To airpump
154 cm
To instruments

FIG 2.—Plan and elevation of tank

was taken as equal to the barometer reading in the open air, plus the difference of level in the U-tube.

Specimen series of measurements. The following table gives a specimen series of measurements made on test-wire No. 2 with $\rho = 100$ ohms in the circuit of galvanometer coil G, and the copper wire R:—

TABLE II

SAMPLE SERIES OF OBSERVATIONS IN FREE CONVECTION TEST

I Air pressure, cm.	II Air pressure. megabars	III I absamp.	IV I^2 absamp.^{2}	V $P = I^2 r_T$ Linear power. abwatts /cm.	VI P_r Linear radiation. abwatts /cm.	VII P_c Linear convections. abwatts /cm.	VIII P_c/θ Linear convection per degree cent. elevation
		$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{5}$	$\times 10^{5}$	$\times 10^{5}$	$\times 10^{3}$
28.8	0.3821	2.84	0.8066	3.182	0.321	2.861	4.87
30.4	0.4030	2.83	0.8009	3.160		2.839	4.83
40.45	0.5365	2.909	0.8462	3.340		3.019	5.14
48.35	0.6420	2.979	0.8874	3.502		3.181	5.42
57.61	0.765	3.060	0.9364	3.694		3.373	5.73
65.15	0.864	3.083	0.9505	3.750		3.429	5.84
65.2	0.866	3.083	0.9505	3.750		3.429	5.84
72.8	0.961	3.10	0.9610	3.792		3.471	5.91
72.85	0.966	3.10	0.9610	3.792		3.471	5.91
165.0	2.193	3.42	1.1696	4.614		4.293	7.31
155.2	2.06	3.36	1.1290	4.454		4.133	7.04
143.8	1.908	3.299	1.0883	4.294		3.973	6.76
143.5	1.907	3.30	1.0890	4.297		3.976	6.77
141.7	1.882	3.375	1.1391	4.494		4.173	7.11
128.9	1.712	3.334	1.1115	4.387		4.066	6.94
116.15	1.542	3.32	1.1022	4.348		4.027	6.85
116.2	1.543	3.318	1.1009	4.344		4.023	6.85
101.5	1.349	3.20	1.0240	4.040		3.719	6.33
101.1	1.344	3.198	1.0227	4.037		3.716	6.33
101.1	1.344	3.194	1.0202	4.024		3.703	6.30
92.75	1.231	3.139	0.9853	3.887		3.566	6.07
92.6	1.229	3.181	1.0119	3.951		3.630	6.30
75.55	1.003	3.092	0.9560	3.772		3.451	5.86
75.6	1.003	3.10	0.9610	3.792		3.471	5.90
75.6	1.003	3.118	0.9722	3.835		3.514	5.98

$G = 1805$ ohms, $G' = 1729$ ohms.

$R' = 0.4248$ ohms, $R = 0.4681$ ohms.

Temperature of tank $t = 18.1$ degrees cent. $= 291$ degrees absolute.

Temperature of wire $T = (t+\theta) = 76.9$ degrees cent. $= 349.9$ degrees absolute.

Temperature elevation of wire $\theta = 58.8$ degrees cent.

Linear resistance of wire at working temperature 3.946×10^6 absohms per cm.

Barometer 29.78 in. (75.64 cm.) at 19 degrees cent.

Column I gives the pressure of the air in the tank in cms. of mercury. Column II gives the pressure in megabars. In Column III, the current strength is given in absamperes. In Column IV appears the absamperes squared. Column V shows linear power dissipated as $P = I^2 r_T$ in abwatts per cm. The linear radiation appears in Column VI. Subtracting the linear radiation from the linear power, we obtain the linear convection in abwatts per cm. The last column gives the last-named result divided by the temperature elevation, or the linear convection per degree centigrade of temperature elevation.

Air-pressures in absolute measure. In Column II of the foregoing table, the air-pressure in the tank is recorded in megabars.* The c.g.s. unit of pressure, 1 dyne per sq. cm. has been called the "bar"; so that a megabar is 10^6 dynes per sq. cm. According to the recently published data of the Bureau International des Poids et Mesures,† a column of mercury 760 mm. (29.92 in.) high, at sea level, in latitude 45 degrees, exerts a pressure of 1.0132 megabars. Consequently 1 megabar represents the pressure of a column of mercury of 750.09 mm. (29.53 in.) under the same conditions. For most practical purposes, therefore, a megabar may be taken as 1 atmosphere. It is actually 0.987 of an atmosphere of 760 mm., at sea level and 45 degrees latitude.

Allowance for linear radiation. The accepted formula for superficial power P_r radiated from a metallic cylindrical surface at a temperature of T_a degrees absolute to surrounding solid substances at a temperature of t_a degrees absolute, is called Stefan's formula:

$$P_r = \sigma (T_a^4 - t_a^4) \qquad \text{abwatts per sq. cm.} \qquad (3)$$

where σ is Stefan's coefficient, which depends upon the surface condition of the radiator. For a "black" body, or a body that emits heat by radiation to the full maximum without any reflection of incident heat, the value of σ has been found by Lummer and Kurlbaum to be 5.3×10^{-5} abwatts per sq. cm. and per degree absolute. On the other hand, a colored body or non-black body, which reflects some radiation and therefore radiates imperfectly, has a smaller Stefan coefficient, which it is necessary to determine experimentally in each case.

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* Richards and Stull. Dec. 1903. New Method for Determining Compressibility. *Carnegie Institution Publ.* No. 7, p. 43.

† Les Récents Progrès du Système Métrique. 1907, pp. 30–31.

In the tests published by one of the writers, in 1889, on copper wires electrically heated in air, the conclusion was reached that, with an ordinary unpolished surface, the wires radiated 0.0786 watt per sq. cm. at 126 degrees cent. to surrounding bodies at 26 degrees cent. Substituting in equation (3), $T_a = 399$, $t_a = 299$ and $P_r = 7.86 \times 10^5$ abwatts per sq. cm., we obtain for bright copper wire $\sigma = 4.5 \times 10^{-5}$ abwatts per sq. cm. and degree absolute.

In allowing for the linear radiation from the wire used in this research, the value taken for σ is 5×10^{-5} abwatts per sq. cm. × degrees absolute. The accuracy of this choice is not of great importance in this case, because the radiation was always small with respect to the convection. Thus in the case presented in Table II, it will be seen that the computed linear radiation from the wire was 0.32×10^5 abwatts per cm. with the above accepted value of σ; whereas the total linear emission varied between 3.18×10^5 and 4.49×10^5 abwatts per cm. Consequently if the Stefan coefficient σ were reduced 50%, or the linear radiation to 0.16×10^5 abwatts per cm., the change thereby effected in the linear convection would be only about 4%. In the case of the larger wire No. 3, the corresponding error would be approximately doubled, and in the case of the smaller wire No. 1, it would be roughly halved. Consequently, if it should be found in future that the Stefan coefficient for such copper wires is materially less than 5×10^{-5} abwatts per sq. cm. and degree absolute, the results for convection arrived at in this paper will not be greatly affected.

If we denote by P the linear dissipation of the test-wire or the power dissipated per linear cm., by P_r the linear radiation, and by P_c the linear convection, we have

$$P = I^2 r_T \qquad \text{abwatts per cm.} \qquad (4)$$

where I is the heating current in absamperes, and r_T the linear resistance at the working temperature T, in absohms per cm.

$$P = P_r + P_c \qquad \text{abwatts per cm.} \qquad (5)$$

$$= \rho \sigma (T_a^4 - t_a^4) + P_c \qquad \text{abwatts per cm.} \qquad (6)$$

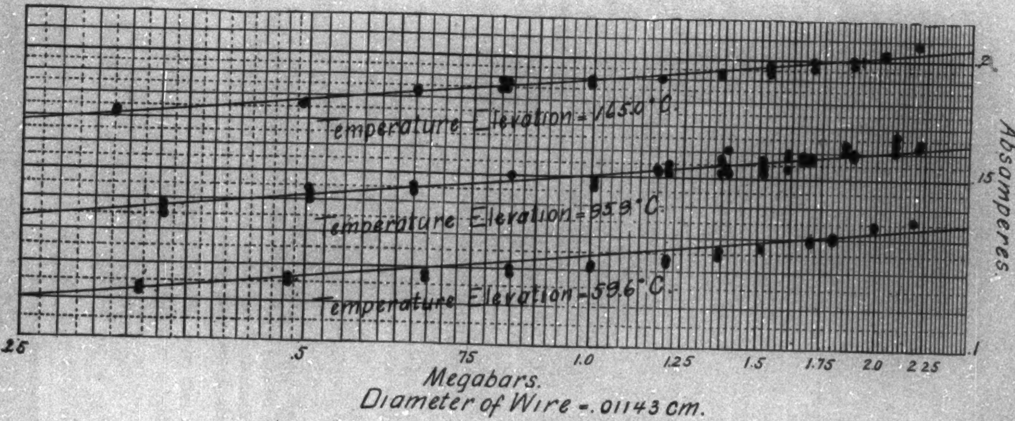

FIG. 3.—Current strengths for varying air-pressures.

where o is the circumference of the wire or its surface per linear cm.

$$P_c = I^2 r_T - o\,\sigma\,(T_a^4 - t_a^4) \quad \text{abwatts per cm.} \qquad (7)$$

Results of measurements with free convection. At different times, thirteen series of observations were made on the dissipation of heat in the tank under varying atmospheric pressures, with the three test-wires specified in Table I. The results of these series are presented graphically in Fig. 3 for wire No. 1, in Fig. 4 for wire No. 2, and in Fig. 5 for wire No. 3. These figures are drawn on logarithmically scaled paper, with ordinates of current strength in absamperes through the test-wire, and abscissas of air-pressure in megabars within the tank. The temperature elevation of the wire θ, in degrees cent., is marked on each line. It will be seen that the observations conform fairly well to straight lines in each case, and that these lines are parallel for different temperature elevations on one and the same wire. This condition represents an equation of the form:

$$I_\theta = B_\theta\, p^m \qquad \text{absamperes} \qquad (8)$$

where B_θ is a constant for each series of observations, and I_θ is the current strength required to be kept flowing through the test wire in order to maintain its temperature elevation θ degrees cent., under an air pressure of p megabars. The tangent of the angle of inclination of the lines with the abscissa axis being equal to the exponent m, we find that for wire No. 1, $m = 0.09$; for wire No. 2, $m = 0.12$, and for wire No. 3, $m = 0.13$; so that the exponent varies with the diameter of the test wire.

In Fig. 6, the results for the three sizes of wire are collected and expressed to logarithmic scale, with ordinates showing linear convection in units of $10^5 \times$ abwatts per cm. and abcissas showing tank air-pressure in megabars. Again, the observations conform fairly well with straight lines, or indicate a relation:

$$P_c = A_\theta\, p^n \qquad \text{abwatts per cm.} \qquad (9)$$

where P_c is the linear convection, or power dissipated in convection per linear centimeter of the test wire, p is the tank air-pressure in megabars, A_θ is a constant for each wire at a given temperature elevation θ degrees cent., and n is an exponent equal to the tangent of the slope of the line. If there were no

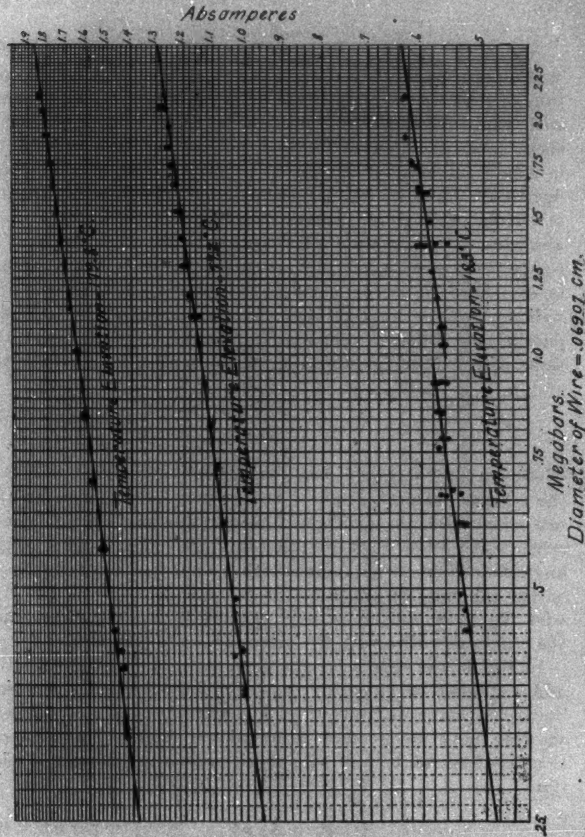

Fig. 4.—Current strengths for varying air-pressures.

radiation to allow for, it would follow that $n = 2m$ for each wire, or the slopes in Fig. 6 would be respectively double those in Fig. 3, 4 and 5. We find, however, for wire No. 1, $n = 0.19$

for wire No. 2, $n = 0.268$, and for wire No. 3, $n = 0.38$, numerical values which approximately satisfy the relation:

$$n = 0.9 \sqrt[3]{d} \qquad \text{numeric} \qquad (10)$$

where d is the diameter of the wire in cm.

If we analyze the values of A_θ in Fig. 6 for the standard air-pressure of 1 megabar (nearly 1 atmosphere), we obtain the results given in the following table.

The foregoing table shows that we may express the linear convection for any one of these wires by the approximate formula:

$$P_c = c\,\theta\, p^{\,0.9\sqrt[3]{d}} \qquad \text{abwatts per cm. and degree cent.} \qquad (11)$$

TABLE III

LINEAR CONVECTIONS PER DEGREE CENT. TEMPERATURE ELEVATION AT THE AIR PRESSURE OF 1 MEGABAR

Diam. of wire cm.	Temp. elevation θ degree cent.	Linear convections at 1 megabar A_θ abwatts per cm.	Linear convection per degree cent. elevation at 1 megabar $c = A_\theta/\theta$	Mean c
0.01143	59.6	2.96×10^5	5,000	5,300
	95.9	4.95 "	5,200	
	165.	9.2 "	5,600	
0.02616	15.1	0.98 "	6,400	5,600
	37.8	1.8 "	4,800	
	46.4	2.45 "	5,300	
	46.8	2.47 "	5,300	
	58.8	3.58 "	6,100	
0.06907	18.3	1.4 "	7,800	8,500
	77.2	6.55 "	8,500	
	179.8	16.7 "	9,300	

where p is the air-pressure in megabars (between 0.15 and 2.5 megabars), d is the diameter of the copper wire in cm. (between 0.01 and 0.07 cm.), θ is the temperature elevation of the wire above ordinary room temperature, in degrees cent., (up to 180 cent.) and c is a quantity which is in the neighborhood of 6000 abwatts per cm. and per degree cent. at 1 megabar, and appears to increase slowly with the diameter of the wire, perhaps in a linear relation:

$$c = a + b\,d \qquad \text{abwatts per cm. and per degree cent., at 1 megabar.} \qquad (12)$$

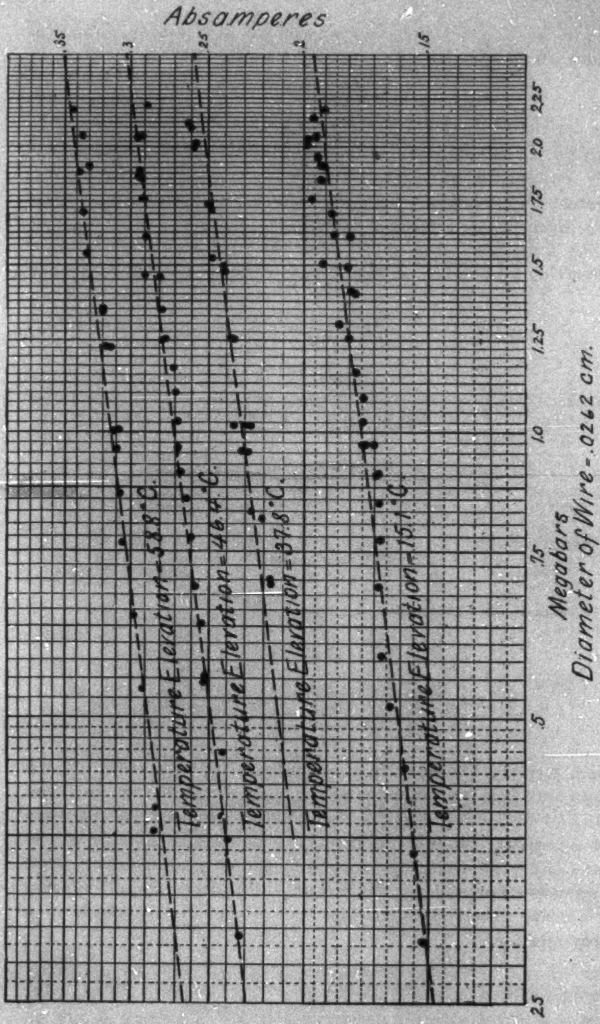

FIG. 5.—Current strengths for varying air-pressures.

As a first approximation we might take:—

$$c = (4+64\,d)\,10^3 \qquad \text{abwatts per cm. and per degree cent., at 1 megabar.} \tag{13}$$

where d is the diameter of the wire in cm.

It is difficult to measure linear free convection from a wire with precision, for the reason that the stream of heated air rising from the wire is very unstable, and is markedly influenced by the presence of slight air-currents, or draughts, in the neighboring atmosphere. Such a wire forms, in fact, a very sensitive draught detector. On the other hand the precision of forced convection measurements is distinctly higher, except at very low wind velocities.

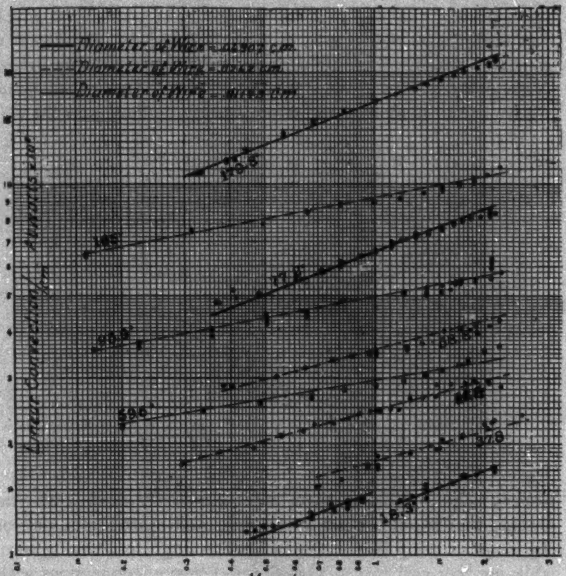

Fig. 6.—Linear convection for different wires at varying air-pressures.

The complete expression of the linear free convection from a thin copper wire supported horizontally in substantially still air was, therefore, from the foregoing results:

$$P_c = (4{,}000 + 64{,}000\,d)\,\theta\,p^{0.9\sqrt[3]{d}} \quad \text{abwatts per cm.} \qquad (14)$$

MEASUREMENTS OF FORCED CONVECTION

General plan. In order to measure forced convection, the test wire was mounted between the prongs of a long fork, which was fastened at right-angles to a shaft driven by a motor at a regulated speed. The test wire was thus forced to move transversely through the air at a known velocity. This was taken as equivalent to a wind of the same velocity moving past the stationary wire. Electric connection was maintained with the moving wire through pairs of slip-rings and brushes, one pair of slip-rings carrying the testing current through the moving wire, while another pair served to maintain pressure connections with taps near the ends of the wire. The wire was maintained at a constant temperature during each series of tests by keeping its resistance constant; that is, by keeping constant the ratio of the potential difference between taps to the testing current, (E/I). The square of the current, multiplied by the linear resistance of the wire at the working temperature, then gave the linear dissipation in the wire at the observed velocity. The linear dissipations reduced by the computed linear radiations, gave the corresponding linear convections at the observed velocities.

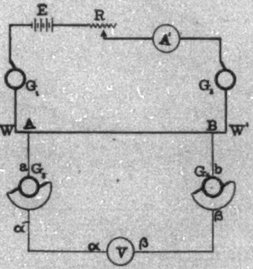

FIG. 7.—Electrical connections used in measurements of forced convection.

Electrical connections. The electrical connections are indicated in Fig. 7. $W\ W'$ is the test-wire in the main circuit of the storage battery E, (from 8 to 15 volts), A' the ammeter, R the controlling resistance, and $G_1\ G_2$ the slip-rings, with their copper gauze brushes. At the points $A\ B$, taps were soldered to the test-wire, and brought into connection with the voltmeter V through the wires Aa, Bb, the slip-rings $G_3\ G_4$, and their copper-gauze double-brushes.

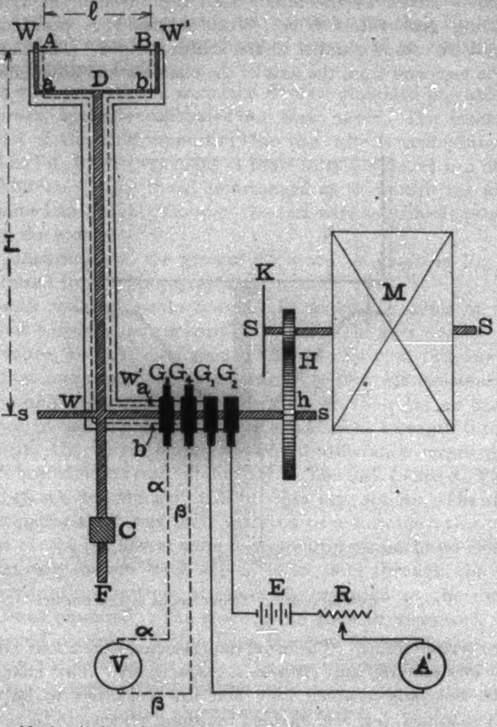

FIG. 8.—Mechanical and electrical connections used in measurements of forced convection.

Mechanical and electrical connections. In Fig. 8, the test-wire *W W′* is shown in place in the fork *D F*, the details of the support being indicated in Fig. 9. This fork is made of a steel tube of 1.9 cm. ($\frac{3}{4}$ in.) external diameter and 1.63 cm. (0.64 in.) internal diameter, 274 cm. (9 feet) long, mounted in the shaft *s s*, which is driven by the motor shaft *S S* through the velocity-reducing gear-wheels *H*, *h*. When adjusted in position, the wire *W W′* stood parallel to the shafts *s s*, *S S*. The radius *L* of the test-wire from the axis of the shaft *s s* was adjustable between certain limits. The usual radii selected were about 118 cm. (46.5 in.) and 180 cm. (70.8 in.), respectively. This change in radius not only enabled high and low velocities to be more easily attained; but also enabled the same velocity to be secured with two radii, as a check upon the observations. A suitable counterpoise *C* had to be used in each case.

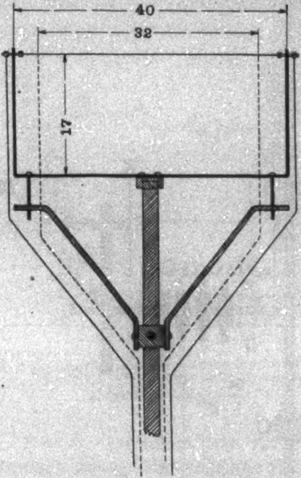

Fig. 9.—Details of fork. Dimensions in centimetres.

The motor *M* was a $\frac{1}{2}$-h.p., 115-volt, 4-pole machine, running at 1200 rev. per min. Its speed of rotation was controlled, in the usual way, by resistances in its field and armature circuits, not shown in the illustrations. The velocity-reducing gear ratio of 18/120, enabled the fork-shaft to make 180 rev. per min., when the motor-shaft made 1200 rev. per min. The four slip-rings were of brass, each 4 cm. (1.57 in.) in diameter, and 1.5 cm. (0.58 in.) wide. The copper gauze brushes resting on them were 3.8 cm. (1.5 in.) long, 0.95 cm. (⅜ in.) wide and 0.67 cm. (0.26 in.) thick. The brushes were soldered to their respective connecting wires, and were spring-pressed into contact with their slip-rings. As an extra precaution, two brushes were used on each of the voltage slip-rings G_3 G_4.

The voltmeter V and ammeter A^1 were standard portable instruments, specially calibrated for these tests. The frame on the end of the fork supporting the test wire is represented in detail in Fig. 9. It was made of brass strip 1.9 cm. (¾ in.) broad and 0.32 cm. (⅛ in.) thick, so arranged as to disturb the air in the immediate neighborhood of the test-wire as little as possible during the motion.

An illustration of the general apparatus is given in Fig. 13, reproduced from a photograph.

Sample series of measurements. In making a series of tests on a test wire, the temperature elevation of the wire was selected in advance, and the resistance of the wire for that temperature elevation was computed by equation (1) from its resistance at the room temperature. A slide-rule was then set to this resistance, in such a manner that for any current strength through the wire, the corresponding potential difference required by Ohm's law could be read off directly. The fork radius L, Fig. 8, was then set, and the motor M brought into action. The speed of the motor-shaft was then adjusted to a suitable value. All speeds except the lowest were measured by means of an electromagnetically driven stroboscopic fork*, and through the slits in its vibrating shutters, a target K, mounted on the motor-shaft, was observed. The speed could thus be measured, with all desired accuracy, within from three to fifteen seconds after bringing the fork to the eye. The current was then increased until the correct current-voltage ratio was obtained, the speed again observed, and all three values recorded.

Each series comprised two different fork radii (L, Fig. 8), in such a manner that both radii were in use over a certain range of speed.

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* The Measurement of Rotary Speeds of Dynamo Machines by the Stroboscopic Fork. By A. E. Kennelly and S. E. Whiting, TRANSACTIONS, American Institute Electrical Engineers, 1908, Vol. XXVII, p. 631.

Table IV contains a sample series of observations.

Column I gives the velocity of the wire, perpendicular to its length, through the air, or the "wind-velocity" using the formula:

$$v = 2\pi L N \qquad \text{cm. per sec.} \qquad (15)$$

TABLE IV

SAMPLE SERIES OF FORCED CONVECTION TEST

Run on wire of 2.038×10^{-2} cm. diameter.

Resistance held at 2.5×10^{6} absohms, giving 128.3 degrees cent. elevation.

Barometer 770.4 mm. @ 18.6 degrees cent.

Average room temperature, 21 degrees cent.

Assmann aspiration psychrometer gave readings for $t = 20.2$ degrees cent. and $t' = 12.6$ degrees cent.

Pressure 6.977 mm. corresponding to 0.905% or 9.05 l. of water-vapor per cubic meter of air.

I	II	III	IV	V	VI	VII	VIII
Wind velocity v cm./sec.	I Abs. amp.	I^2 Abs. amp.^{2}	$P = I^2 r_T$ Linear power Abwatts/cm.	P_r Linear radiation Abwatts/cm.	P_c Linear convection Abwatts/cm.	P'_c/θ Linear convection per degree cent. elevation	$k = P'_c/(\theta\sqrt{v})$ Linear convection per degree cent. elevation and per $\sqrt{v}$
	$\times 10^{-1}$	$\times 10^{-1}$	$\times 10^{6}$		$\times 10^{6}$	$\times 10^{4}$	10^{2}
0	3.4	1.156	0.903	7.763×10^{4}	0.825	0.643	
114	5.6	3.136	2.450		2.372	1.849	1.731
205.7	6.2	3.844	3.003		2.926	2.280	1.591
330.5	6.8	4.624	3.613		3.535	2.755	1.515
522	7.5	5.625	4.394		4.316	3.364	1.472
395	7.05	4.970	3.884		3.807	2.967	1.493
561	7.5	5.625	4.394		4.316	3.364	1.420
708	8.0	6.400	5.000		4.923	3.837	1.442
880	8.5	7.225	5.645		5.567	4.340	1.463
1113	9.05	8.190	6.400		6.322	4.928	1.477
1321	9.42	8.874	6.931		6.853	5.342	1.470
775	8.3	6.889	5.382		5.305	4.135	1.485
1072	9.0	8.100	6.328		6.250	4.872	1.488
1383	9.55	9.120	7.127		7.049	5.494	1.477
1632	9.95	9.900	7.734		7.656	5.968	1.477
1862	10.35	10.712	8.368		8.291	6.463	1.498
0	0	1.225	0.957		0.879	0.685	

where L is the fork radius (Fig. 8) in cm., N is the speed of the fork-shaft in rev. per sec., and v is the wind-velocity in cm. per sec.

Column II gives the observed current, in absamperes through the wire, required to maintain its correct linear resistance in absohms per cm. at the working temperature T degrees cent.

Column III gives the current squared, expressed in absamperes squared. Column IV gives the linear dissipation in abwatts per cm. ($P = I^2 r_T$). Column V gives the linear radiation computed from the formula:

$$P_r = o\,\sigma\,(T_a^4 - t_a^4) \quad \text{abwatts per cm.} \qquad (16)$$

where o is the circumference of the wire in cm., σ is Stefan's coefficient, taken as 5×10^{-5} abwatts per sq. cm. and degree absolute. T_a is the absolute working temperature of the wire, and t_a the absolute temperature of the surrounding air. Column VI gives the linear convection $P_c' = P - P_r$, obtained by deducting the computed radiation from the linear dissipation. Column VII gives P_c'/θ or the linear convection divided by the inferred temperature elevation of the test-wire. The last column gives $P_c'/(\theta\sqrt{v})$ or the quotients obtained by dividing P_c'/θ by the square root of the wind velocity. It will be observed that except for the lowest wind velocity of 114 cm. per sec. the entries in the last column are seen to be substantially constant near 1.497×10^3.

TABLE V

PARTICULARS OF COPPER WIRES USED IN MEASUREMENTS OF FORCED CONVECTION

Wire No.	Diameter		Length between taps cm.	Cross-sectional area cm.²	Linear surface cm.²	Linear resistance @ 20 degrees cent. absohms/cm.	Linear resistance @ 0 degrees cent. absohms/cm.	Resistivity @ 0 degrees cent. absohm-cm.
	Cm.	Inches						
1	0.01008	0.004	32.5	0.7971×10^{-4}	3.167×10^{-2}	2.18×10^{7}	2.011×10^{7}	1603
2	0.0159	0.0063	31.6	1.985 "	4.995 "	0.8703 "	0.8028 "	1594
3	0.02038	0.008	32.0	3.262 "	6.402 "	0.5219 "	0.4815 "	1600

Copper wires. The accompanying table presents the dimensions of the copper wires employed in the measurements of forced convection.

Correction for linear radiation. It will be observed that in the case presented in Table IV, the computed linear radiation P_r' is only 3% of the linear dissipation P at the lowest recorded speed—114 cm. per sec.—and is only about 1% of the linear dissipation at the highest recorded speed—1862 cm. per sec.

This is a fair sample of the relation between the linear radiation and dissipation for all of the wires used. It shows that whereas the error due to incorrect estimation of σ, which might enter into the results for free convection, would be small but appreciable, the corresponding error in the results for forced convection would be practically quite inappreciable.

Results of measurements of forced convection. Out of the 16 series of measurements at different dates on the three test wires, all of which are in good agreement, 10 series are plotted on the logarithmically scaled chart shown in Fig. 10. The ordinates are in current units of amperes, or of 10^{-1} absamperes, (2 to 20 amperes) and the abscissas in units of wind-velocity of 10^2 cm. per sec., (200 to 2000 cm. per sec.). It will be observed that, except at the lowest velocities, the observations conform closely to straight lines whose inclinations with the abscissa axis are all 14°, or $\tan^{-1} 0.25$; so that the observations indicate a relation

$$I_\theta = K_\theta \sqrt[4]{v} \qquad \text{absamperes} \qquad (17)$$

in which K_θ is a constant for each wire and temperature elevation θ. The diameter of the wire is indicated by the type of line in Fig. 10, and the temperature elevation of the series in degrees cent. is marked on each line.

In Fig. 11 the results for the same ten series are plotted as linear convections in ordinate units of 10^6 abwatts per cm., against wind-velocity in abscissa units of 10^2 cm. per second. The lines are here inclined at an inclination of $26\frac{1}{2}° = \tan^{-1} 0.5$, and the results indicate a relation for linear convection:

$$P_c' = K_\theta' \sqrt{v} \qquad \text{abwatts per cm.} \qquad (18)$$

where K_θ' is a constant for each size of wire and temperature elevation θ.

Equations (17) and (18) cease to hold below wind velocities of 200 cm. per sec., apparently for the reason that these equations require zero linear convection at zero wind velocity, or stationary air. But free convection continues under the latter condition; so that these equations fail at low velocities by ignoring the influence of free convection.

The following table summarizes the results for the ten series of observations presented graphically in Figs. 10 and 11.

Column III gives the temperature elevation in degrees cent.
" IV " " linear convection from Fig. 11 for $v =$ 900 cm./sec.
" V " $K_\theta' = P_c'/\sqrt{900} = P_c'/30$ abwatts per cm and cm./sec.
" VI " $k = K'/\theta$ abwatts per cm. for unit speed and 1 degree cent. elevation.

It appears, therefore, that for wire No. 1 the linear convection is:

$$P_c' = 884\,\theta\sqrt{v} \qquad \text{abwatts per cm.} \qquad (19)$$

TABLE VI

I Test wire No.	II Diameter. cm.	III Temperature elevation. θ deg. cent.	IV Linear convection P'_c for $v = 900$. abwatts/cm.	V K'_θ for $v = 900$. abwatts/cm	VI k abwatts per cm. and deg. cent. elevation	VII Mean k
1	0.01008	106.05	2.81×10^6	0.9366×10^5	883	884
		179.	4.63 "	1.547 "	864	
		251.8	6.83 "	2.277 "	904	
2	0.0159	117.4	4.16 "	1.387 "	1181	1212
		211.1	7.74 "	2.58 "	1222	
		305.	11.28 "	3.76 "	1233	
3	0.02038	51.	2.225 "	0.7416 "	1454	1475
		128.3	5.76 "	1.92 "	1497	
		205.5	9.08 "	3.027 "	1473	
		282.8	12.52 "	4.173 "	1476	

for wire No. 2:

$$= 1212\,\theta\sqrt{v} \qquad \text{abwatts per cm.} \qquad (20)$$

and for wire No. 3:

$$= 1475\,\theta\sqrt{v} \qquad \text{abwatts per cm.} \qquad (21)$$

Consequently, between the limits of $v = 200$ and $v = 2000$ cm. per sec. (4.5 and 45 miles per hour), and up to temperature elevations of 300 degrees cent., the linear forced convection is expressed by

$$P_c' = k\,\theta\sqrt{v} \qquad \text{abwatts per cm.} \qquad (22)$$

where k increases nearly in direct proportion to the diameter. A first approximation to the forced linear convection for a small wire of diameter d cm. would be:

$$P_c' = 76{,}000\, d\, \theta \sqrt{v} \qquad \text{abwatts per cm.} \qquad (23)$$

If we attempt a second approximation, which will more nearly satisfy equations (19) (20) and (21), we obtain:

$$P_c' = (300 + 58{,}000\, d)\, \theta \sqrt{v} \qquad \text{abwatts per cm.} \qquad (24)$$

Influence of water vapor in the air upon forced linear convection. On the occasion of each series of observations, a measurement of the amount of water-vapor in the air of the room was made by means of an Assmann psychometer, in which a fan driven by clock-work forces air over the wet and dry bulbs of a pair of thermometers placed side by side. The amount of water-vapor varied between 5.8 and 13.8 liters per cubic metre, on different days.

One or two measurements were taken with the air almost completely saturated with moisture after boiling water in the room for some hours. The object was to ascertain whether the presence of the water-vapor in excess appreciably altered the linear forced convection. It was found that starting with a clean test wire 0.0159 cm. in diameter, worked at 70 degrees cent. elevation in normally dry air, at a barometer reading of 778 mm., the series obtained was

$$P_c' = 1255\, \theta \sqrt{v} \qquad \text{abwatts per cm.} \qquad (25)$$

The next day, with moisture-saturated air and a barometer reading of 772 mm., the series obtained was about

$$P_c' = 1210\, \theta \sqrt{v} \qquad \text{abwatts per cm.} \qquad (26)$$

At first sight the reduction of about 4% seemed attributable to the excess of water-vapor; but it was found that the test wire had become decidedly blackened and superficially oxidized by being driven in the moist air. On repeating the series on the day following, with the same wire in normally dry air, at a barometer reading of 765 mm., the series obtained was:

$$P_c' = 1210\, \theta \sqrt{v} \qquad \text{abwatts per cm.} \qquad (27)$$

or the same as in the saturated air. Consequently, the effect of moisture in the air was relatively small, and was masked by the influence of changes in surface condition of the test wire or changes in the barometric pressure. The observations have not yet even served to determine whether the linear forced convection is increased or diminished by the presence of water-vapor.

Correction for free convection at low wind velocities. If formulas (23) and (24) are applied to the case of the test wire at rest and subject only to free convection, using the value of k obtained with higher wind velocities, we obtain a certain fictitious value of v which may be called the virtual wind-velocity of free convection. It is a matter of interest to examine this virtual velocity in the different series of observations. They are presented in the following table:

TABLE VII

VIRTUAL WIND VELOCITIES OF FREE CONVECTION FOR DIFFERENT TEST WIRES

I Diameter of test wire cm.	II Temperature elevation θ degree cent.	III Constant k abwatts/cm. per degree cent. and unit velocity	IV Linear free-convection $v = 0$ abwatts per cm. and degree cent.	V Virtual wind velocity v' cm. per sec.	VI Mean v' cm. per sec.
0.01008	106.05	883	4640	27.5	27.5
	"		4790	29.3	
	"		4438	25.4	
	179	864	3968	21.1	
	"		4794	30.7	
	251.8	904	4739	27.5	
			5042	31.0	
0.0159	117.4	1181	5269	20.0	22.9
	"	"	5420	21.0	
	117.4	"	5395	20.8	
	"	"	5777	23.8	
	211.1	1222	6072	24.7	
	"	"	5850	22.9	
	"	"	5850	22.9	
	305	1233	6016	23.7	
	"	"	6660	29.1	
0.02038	51	1454	5515	14.4	20.7
	"	"	6354	19.1	
	128.3	1497	6434	18.5	
	"	"	6855	21.0	
	205.5	1473	6818	21.5	
	"	"	7196	23.8	
	282.8	1476	7018	22.6	
	"	"	7378	25.0	

Column II gives the temperature elevation of the test, column III the values of k deduced for that test in Table VI. The linear convection per degree cent. elevation with the wire at rest is given in Column IV. This is linear free convection; but, treating the convection as though it were due to wind velocity, we obtain the values of the virtual wind velocity given in Column V, with the mean values for each wire in Column VI. It appears that the virtual wind velocity is independent of the temperature elevation and that it is about 23 cm. per second. It is independent of the size of wire to a first approximation; but is slightly lowered by increasing the wire diameter.

If we increase all the actual wind velocities by 25 cm. per second, so as to correct for free convection, we obtain an empirical formula which conforms satisfactorily with the observations not only between the speed limits of 200 and 2000 cm. per sec., but also down to zero speed. We obtain from (23):

$$P_c' = 76{,}000\, d\, \theta \sqrt{v + 25} \qquad \text{abwatts per cm.} \qquad (28)$$

or taking formula (24) as more nearly representing the observations, we have:

$$P_c' = (300 + 58{,}000\, d)\, \theta \sqrt{v + 25} \qquad \text{abwatts per cm.} \qquad (29)$$

Possible application to anemometry. The law indicated by the results above stated, that the linear forced convection from a thin copper wire is proportional to the temperature elevation and to the square root of the wind velocity, after allowing a small correction for free convection, may be capable of application to the measurement of wind-velocities. It would probably be necessary to maintain a constant surface condition for the test wire by gilding or platinizing it, in order to keep the wire from oxidizing. A short vertical test wire carrying, say, constant-current strength under 110 volts, and with a steadying resistance of German-silver in its circuit, to absorb all but 6 volts, would fall in temperature and in resistance with an increase of the horizontal component of the wind. A recording voltmeter, connected to pressure taps near the ends of the test-wire, would leave a record that would be interpretable in wind-velocity. The instrument would have the maximum sensitiveness at low wind velocities and the sensitiveness would diminish as the wind velocity increased. Or, the test-wire might be worked at constant voltage of, say, 6 volts from a storage battery, and a recording ammeter in circuit with the wire would leave a record interpretable in wind velocity.

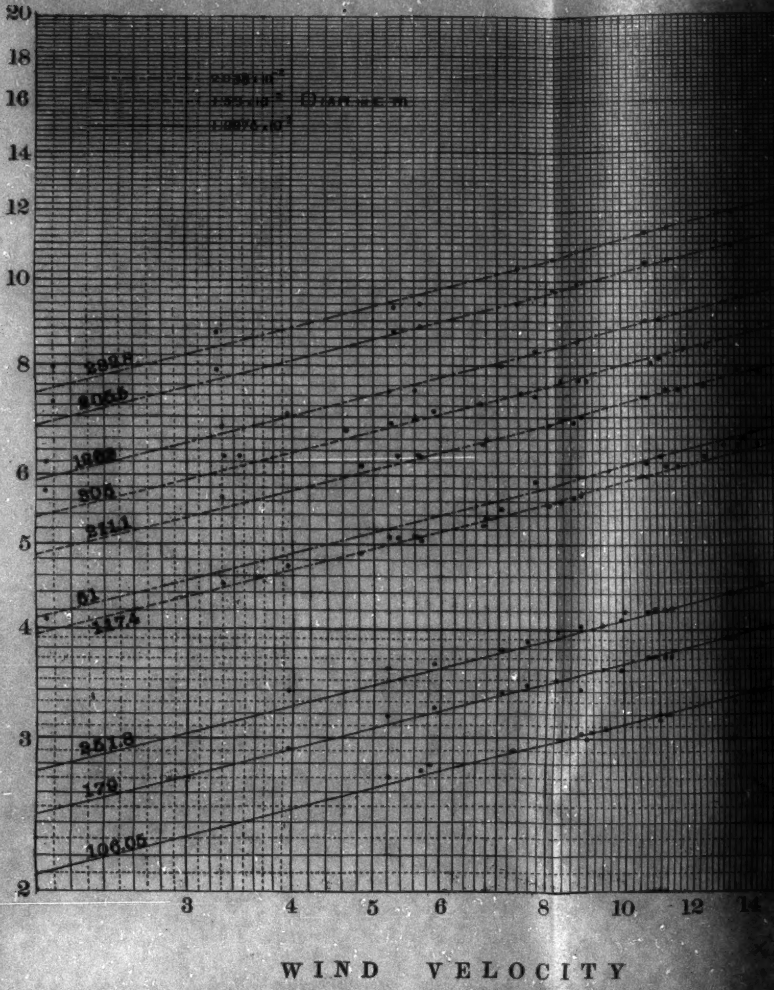

Fig. 10.—Current strengths required to maintain constant temperature elevation in wires under

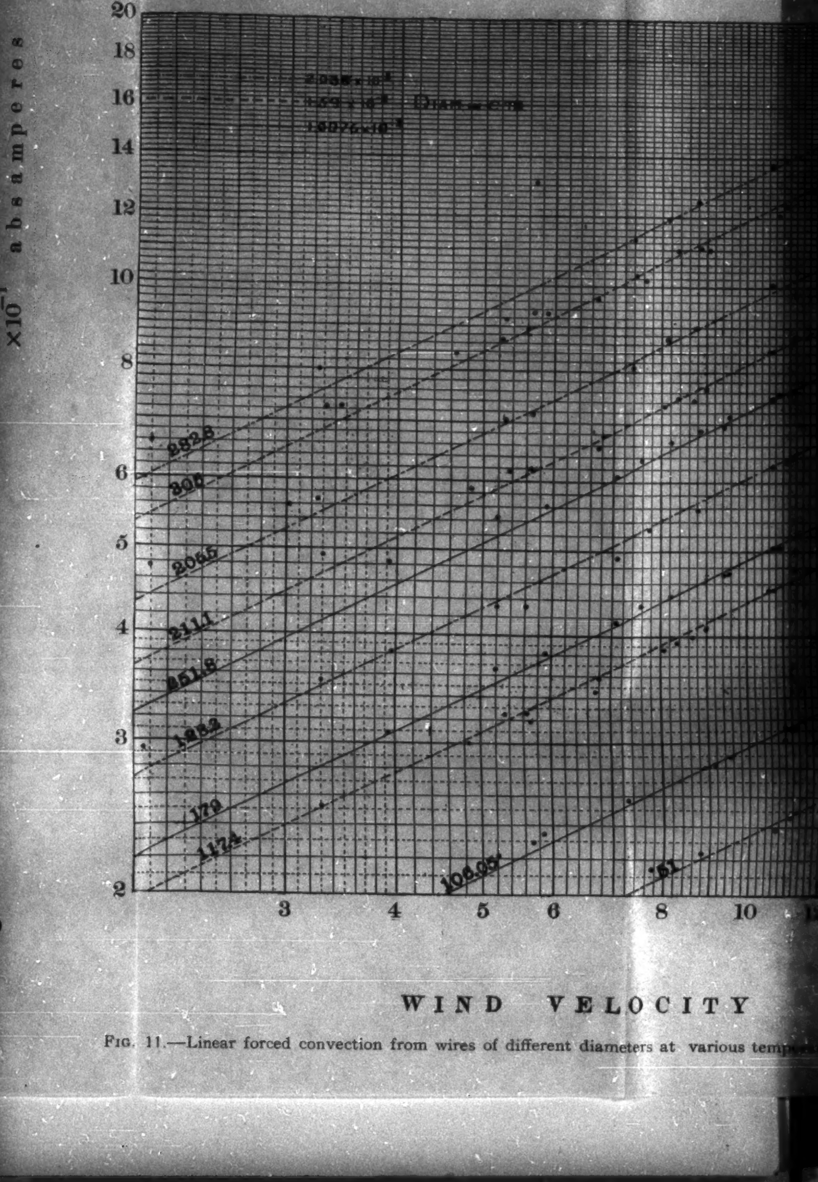

FIG. 11.—Linear forced convection from wires of different diameters at various temp

Summary of experimental results. From the measurements above described on the dissipation of heat from thin copper wires (diameters 0.1 to 0.7 mm., or 4 to 27 mils) the following facts may be stated for conditions of free convection in a tank:

At constant standard air-pressure of 1 atmosphere, the linear convection was proportional to the temperature elevation of the wire, and was in the neighborhood of 6,000 abwatts (6×10^{-4} watt) per linear cm. per degree cent. and, to a first approximation, independent of the size of wire, although increasing slowly with the diameter. The results do not yet warrant a decision as to the precise increase with diameter, but it represented about $4{,}000 + 64{,}000\,d$ abwatts per cm., where d is the diameter in cm.

FIG. 12.—Apparatus in free convection tests.

Under varying atmospheric pressure, the linear convection increased with the pressure, substantially according to an exponential law, or to a straight line on logarithm paper, the exponent being the same for the same wire at different temperature elevations but with different wires increasing slowly with the diameter of the wire, or, to a first approximation, as the cube root of the diameter.

The current strength required to maintain a wire at constant temperature under free convection in varying atmospheric pressure, followed an exponent of the pressure, or a straight line on logarithm paper, the exponent being the same for different temperature elevations (up to 180 degrees cent.) of the same wire, but increasing slowly with the diameter of the wire.

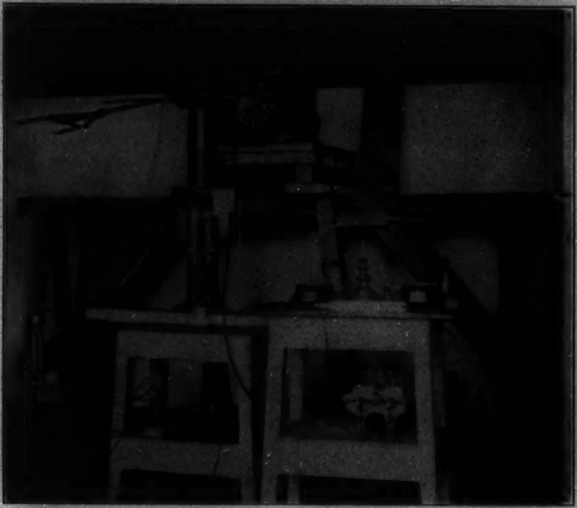

Fig. 13.—Apparatus in forced convection tests.

For conditions of forced convection, or wind, on a thin wire, the following observations may be stated:

The linear convection was proportional to the temperature elevation of the wire at the same wind velocity.

The linear convection, at any single wind velocity between 200 and 2000 cm. per second, increased with the size of wire and, as a first approximation, in direct proportion to the wire diameter.

Under varying wind velocities, within the range of 200 to

2000 cm. per second, the linear convection increased as the square root of the wind-velocity.

At wind-velocities below 200 cm. per second, the linear convection was greater than that predicted by the last preceding rule, apparently owing to the presence of free convection in air not moved by an external force.

The free convection from the wires at rest corresponded to a forced convection at a virtual wind-velocity of about 25 cm. per second. To a first approximation this virtual wind velocity of free convection was constant for the different temperature elevations, and also for the different sizes of thin wire tried; but it diminished slightly as the diameter of the wire increased.

The correction for radiation on a wire of 0.2 mm. diameter in a wind velocity of 500 cm. per second was less than 2 per cent.

The linear convection from a wire under a wind velocity of 2000 cm. per second was nine times that when the wire was at rest.

If a virtual wind velocity of 25 cm. per second, for free convection, be added to all the actual wind velocities in forced convection tests, the linear convections conform satisfactorily to the law of square roots of wind velocity from 2000 cm. per sec. down to 0 cm. per sec.

A thin layer of oxide on the wire slightly diminished the forced convection.

LIST OF SYMBOLS EMPLOYED

A_θ, B_θ = constants of linear free convection, abwatts and absamperes per cm. at 1 megabar.

a, b, c = constants of linear free convection, abwatts per cm. per degree cent. at 1 megabar.

d = diameter of test-wire, cm.

$G\, G'$ = resistances of differential galvanometer coils, ohms or absohms.

I_θ = current strength in test-wire at θ° cent, temperature elevation, absamperes.

$K_\theta\, K_\theta'$ = constants of linear forced convection, absamperes and abwatts per cm. at 1 cm. per sec.

k = constant of linear forced convection, abwatts per cm. per deg. cent., at 1 cm. per sec.

N = rotary speed of fork-shaft, rev. per sec.

m, n = exponents of the atmospheric pressure, numerics.

o = circumference of a test wire, cm. = linear surface of a test wire, sq. cm. /cm.

p = atmospheric pressure, megabars.

R = resistance of test wire, ohms or absohms.

R' = Constant comparison resistance of German silver, ohms or absohms.

R_0 = Resistance of a test wire at 0° cent., absohms.

R_T = Resistance of a test-wire at T° cent., absohms.

r = Linear resistance of a test-wire, absohms.

r_T = Linear resistance of a test-wire at T degrees cent., absohms.

ρ = adjustable resistance in galvanometer circuit, ohms, or absohms.

σ = Stefan's coefficient, abwatts per sq. cm. per degree absolute.

$P = I_0^2 r$ = linear dissipation of power in test-wire, abwatts per cm.

P_c = linear free convection from test-wire, abwatts per cm.

P_c' = linear forced convection from test-wire, abwatts per cm.

P_r = linear radiation from test-wire, abwatts per cm.

T_a = Temperature, in degrees absolute, of test-wire.

T = Temperature, in degrees cent., of test-wire.

t_a = Temperature, in degrees absolute, of surrounding bodies.

t = Temperature, in degrees cent., of surrounding bodies.

$\theta = T - t$ = Temperature elevation, degrees cent., of hot wire.

t' = Temperature in degrees cent. of wet bulb thermometer.

v = velocity of wind, cm. per second.

v' = virtual wind-velocity of free convection, cm. per second.

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Discussion on "The Convection of Heat from Small Copper Wires." Frontenac, N. Y., June 28, 1909

V. Karapetoff: Dr. Kennelly uses the absolute electromagnetic system of units, and besides he uses the abbreviation "abs." for absolute. I have always found this system of notation to be very convenient, as well as the notation "*abstat*" for absolute electrostatic units. But while fully appreciating the convenience of the use of the absolute system in some cases, I would like to ask Dr. Kennelly the reason for using this system in this paper? For instance, referring to Table I, or to any other Table in the paper, it will be seen that the current values could just as well have been expressed in ordinary amperes, because they come very distinctly within the range of amperes. In the same way Dr. Kennelly measures resistance in absohms, or absolute ohms, then multiplies by 10^{-9}, and finally gets ordinary ohms.

I would also like to ask the reason for introducing such unfamiliar units as megabars for pressures, when they could have been expressed in atmospheres, or, to be more consistent, in metric atmospheres (one metric atmosphere is one kilogram pressure per square centimeter)? I see that power could not be expressed conveniently in watts in this case, but I do not see why abwatts or absolute watts could not be employed, or, still better, milliwatts or microwatts, which every electrical engineer would understand.

Dr. Kennelly calls formulas (8) and (9) *exponential*. I think it more correct to call them *parabolic*. What is known as an exponential expression is of the form $y = Ce^{\mp x}$; there are several phenomena in physics and in engineering that follow this exponential law. The expression used in the paper is of the form $y = Cx^n$, and it would be more consistent to call it a parabolic law. However, this is a minor point, provided the distinction be clearly understood.

Formula (28) is rather a common form of a law that is met with in engineering; that is to say, where one variable varies as a certain power of another variable, and then there is a correction term, in this case = 25 (correction for free radiation). If it were not for the correction term, the coefficients of the formula could be easily evaluated from the results of experiments, using logarithmic paper. I would ask Dr. Kennelly if there is any method by means of which formulas (28) and (29); that is, those containing a correction term, could also be handled by means of logarithmic paper; or do we have to go back to the laborious method of least squares?

Charles P. Steinmetz: I have given considerable attention to the study of a rational reduction of empirical phenomena and have also found the feature mentioned by Professor Karapetoff, the existence of a constant term, a great annoyance when using logarithms to derive a parabolic law. But I have found that with a little experience the method can still be used. If the logarithmic line is curved slightly, concave or convex, it signifies a positive or negative constant term. Subtracting or adding a constant term to the function, and replotting, produces a second logarithmic curve. If this has the same curvature, it indicates that the constant term is too small; if it has the opposite curvature, by interpolating between the two logarithmic curves there results a value of the constant term which gives minimum curvature. Where necessary, by a second interpolation, a still closer approximation can be obtained, thereby evaluating a parabolic function with constant terms. This appears to me the simplest method. If any one knows of a simpler method I shall be glad to hear of it, because the quick evaluation of empirical curves is frequently of great importance.

Chas. F. Scott: I would reinforce what has been said about the nomenclature in this paper. The facts set forth are engineering facts, which should be known and appreciated and understood by ordinary engineers as well as by scientists. I am inclined to think that some people who may want to use this paper would be apt to interpret "abs" as meaning absurd. Dr. Kennelly himself, in presenting the paper, in order that those present may have some conception of what he is talking about, says in one place "that is approximately equal to one atmosphere." The term "megabar" conveys very little information to the average engineer, and other strange names are equally perplexing.

Appearances to the contrary, the paper is not abstruse, nor does it deal with the mysterious. It deals with phenomena which are matters of ordinary experience and for which there is an adequate, everyday language. Without questioning the excellence of the absolute system of units, I fail to see its utility in the present case. Even if it were conceded useful to call an ampere or a watt by some other name, why should we mystify the barometric pressure by some unfamiliar term that means nothing to most of us? So far as I see there is no fundamental relation in these tests requiring absolute units to express the watts of the atmospheric pressure—the latter is simply recorded as a condition under which the tests are made and its value does not enter into any formula any more than does the serial number of the test.

Another point, if I understand correctly; Dr. Kennelly points out in the main test that the curves showing the relation between convection and wind velocity cannot be drawn down to zero; they would tend to show zero as convection of heat at zero speed although there is, of course, a considerable loss. Now the speed that is really involved is not the absolute speed of the wire, but the relative speed between the wire and the air. When the wire is stationary, there really is some breeze created by the natural rise of air passing the wire. The natural draft caused by the rise of the hot air when the wire is actually stationary in regard to surrounding objects, may result in an actual velocity with respect to the air, which possibly accounts for the apparent discrepancy. Possibly we could get the zero point; that is, the zero of relative motion between wire and air, by raising the wire at a definite speed so that the wire is continuously surrounded by the same air.

Paul M. Lincoln: I would like to express my appreciation of the data which Dr. Kennelly has presented in this paper. The engineer who is designing electrical apparatus is confronted at once with the questions: 1. How much heat can be radiated from the surface of this apparatus with a given temperature? and 2. How is the law of radiation changed by forced ventilation? The data which Dr. Kennelly has presented here give the best answer to those questions that I know of.

In this paper Dr. Kennelly gives data as to the rate at which heat is dissipated from bare metallic surfaces. The designing engineer is particularly interested in the rate at which insulated surfaces will dissipate heat. A study of the changes, if any, which will be introduced into the values determined by Dr. Kennelly by covering bare surfaces with the ordinary types of insulation would be of great assistance to the designing engineer. I hope that he will give us the result of such study at some future meeting.

A. E. Kennelly: In regard to the matter of "abs" and "abwatts", an apology is offered for the names, which are slang, but I offer no apology for using the C. G. S. system. Our reason for using the C. G. S. system in this case is that we have to deal with certain fundamental physical effects. This is a physical paper, rather than an electrical engineering paper. This report is only a first step towards electrical engineering.

It is true that we actually used ammeters, worked with amperes, and put them back into absamperes, in the manner Professor Karapetoff pointed out. We thought it simpler to keep to one and the same system of units, and not to oscillate between practical and absolute units. We may have been wrong in taking the absolute system as our choice, but having once adopted it, I think we were right in adhering to it.

I think Professor Karapetoff is right as to the term "parabolic." We should have said parabolic instead of exponential. We should have been glad to adopt that amendment in terminology.

In regard to what Mr. Scott has pointed out, the reason we chose the *megabar* is because it is the C. G. S. unit of pressure, one megadyne per square centimeter. If we are going to use C. G. S. units at all, we must use them throughout in order to be consistent. I do not think we should have gained in simplicity of statement if we had tried to define an atmosphere with equal precision in the ordinary system.

The remarks of Mr. Scott in regard to the matter of the virtual velocity of free convection are very pertinent and seem likely to be correct, but we did not dare to say that. We do not know that the velocity of the air past the wire was twenty-five centimeters per second. The formula which we give to include the virtual velocity of free convection is an empirical formula, but we hope it may be possible to demonstrate that the formula is rational, as Mr. Scott suggests.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

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ALTERNATOR FOR ONE HUNDRED THOUSAND CYCLES

BY E. F. W. ALEXANDERSON

Before entering into a description of the form of generator dealt with in this paper, it may be of interest to give a short review of the history of the high-frequency alternator. Heretofore the 10.000-cycle machine has represented the highest frequency in commercial use. Such a machine was designed by Steinmetz in 1900 and a number of them are now in service. A similar machine for 10,000 cycles was described by Lamme in a paper before the Institute in 1904.* Reference may be made particularly to a paper by Dudell read before the Physical Society of London, giving a synopsis of his work with this kind of apparatus and describing the experiments made by him.

In 1904 when the author began to develop for Professor Fessenden, an alternator which should have a frequency of about 100,000 cycles and an output sufficient for commercial work in wireless telegraphy, not much confidence was placed in the possibility of constructing such a machine. The doubts expressed in the discussion of Dudell's paper as to the practical application of such machines to wireless telegraph work seemed quite just, in view of the fact that the highest frequency that had been produced with any appreciable output was 10,000 to 15,000 cycles, while Dudell's machine, which had been worked up to 120,000 cycles, had an output of a fraction of a watt.

Since then three machines of the design described in the following pages, and referred to in several papers by Professor Fessenden, have been placed in service. In this paper there will be described a perfected form of the same general type, rated at 2 kw. and 100,000 cycles.

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* TRANSACTIONS A.I.E.E., 1904 Vol. XXIII. p. 417.

Early types. The stages of development which led to the present type of machine were substantially the following:

In view of the special precaution which had to be taken to reduce the core loss in the alternator built for 10,000 cycles, it was natural in the first attempts at building a machine for 100,000 cycles to try to eliminate the iron in the armature.

The first machine built was a model with a revolving armature of the Ferranti type, 3 in. in diameter. The experiment was encouraging, inasmuch as it demonstrated the possibilty of generating an appreciable amount of power at 100,000 cycles, but the machine could never be brought up to a corresponding speed on account of mechanical difficulties. The armature had 200 conductors consisting of 100 U-shaped phosphor-bronze wires anchored in insulated segments clamped in the rotating body. As long as the machine was run at no load, it acted comparatively well. The centrifugal force and air pressure on both sides of the wires seemed to keep them away from the stationary pole faces; but as soon as the field was applied the magnetic action on the current in the conductors was sufficient to distort the wires so that they would strike the poles and break.

From this experience it was apparent that a successful machine must have a stationary field winding as well as a stationary armature and that the armature should not contain any iron. The outcome of these conditions was a type of machine illustrated in Fig. 1. The armature is made of wood and the two rotating discs form a complete magnetic circuit which is energized by a stationary field coil suspended inside the armature between the discs. In connection with this machine a number of mechanical problems were to be solved, which will be referred to when describing the latest form of the alternator. The chief reason why this machine could not be considered as the final development was the fact that the rotating discs could not be made symmetrical. Owing to this fact the centrifugal force at high speed changed the shape of the discs in such a way that the air-gap between the field and the armature was increased; the result being that the voltage of the generator did not increase in proportion to the speed, but reached a maximum at about 60,000 cycles and decreased at higher speed.

Type of construction. Fig. 2 shows the construction arrived at in a machine recently completed. As there was a question whether it was practicable to use an iron armature at a frequency of 100,000 cycles, the machine was built with two kinds of armatures for trial, one of iron and one of the winding placed in wood. The iron proved to be preferable, giving a higher output and a better mechanical structure. The success of the iron armature is largely due to the fact that the volume of iron subject to alternating flux is extremely small. The main part of the laminated armature carries a constant flux, while the pulsating flux occurs only in the teeth that separate the armature conductors.

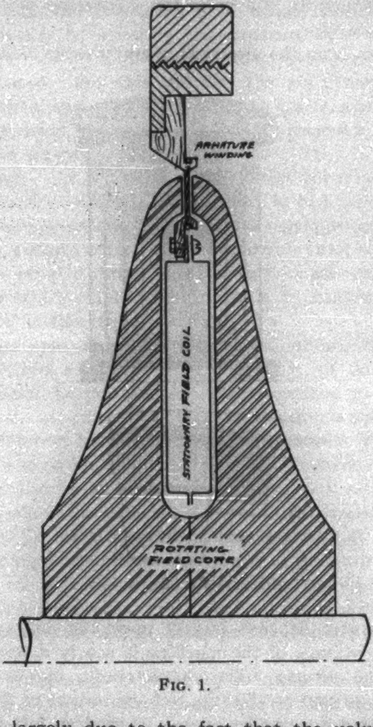


FIG. 1.

The alternator shows in every way the same characteristics as a generator of moderate frequency. The following are the constructional data of the machine: the armature has 600 slots with one conductor per slot of 0.016 copper wire, triple-silk covered, and varnished. The wire is wound in a continuous wave up and down in the successive slots. The rotating field has 300 projections, which, as the machine is of the inductor type, correspond to 600 poles for a machine of the ordinary alternate-pole type.

It appears from the electrical characteristics that the output of the generator depends largely upon the air-gap clearance, because the voltage of the machine is nearly inversely proportional to the air-gap. The characteristic curves have been given at an air-gap of 0.015 in. but the output of the generator can be doubled if a smaller air-gap be used; in fact the machine has been operated with an air-gap as small as 0.004 in., though such a clearance would not be practicable for continuous operation. In view of this condition it is desirable to regulate the air-gap so as to offset any wear in the bearings, and to select the gap which is suitable for the work to be done. If the machine

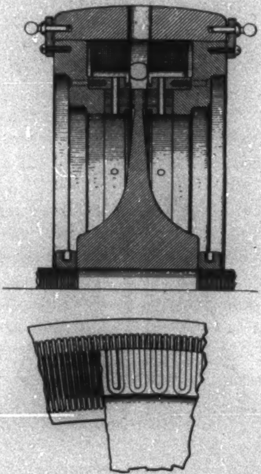


FIG. 2.

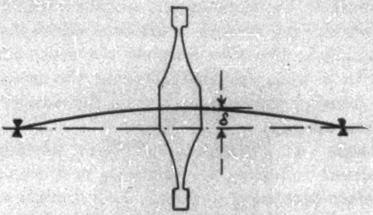
is to be operated continuously without attention, a comparatively large clearance is necessary, while for a special experiment in which higher power is required a small gap may be used.

The sensitiveness of the air-gap regulation is one of the reasons why, instead of using the usual drum winding construction of the armature, the winding was applied on a radial face, as shown in Fig. 2. The armature is mounted on a frame that is threaded into the stationary field frame, and the air-gap can be set exactly by screwing the armature tight against the disc and then moving it back a distance corresponding to the desired clearance. For this purpose the stationary frame is provided with a scale, so that rotating the armature on its thread one division corresponds to one thousandth of an inch change of the air-gap.

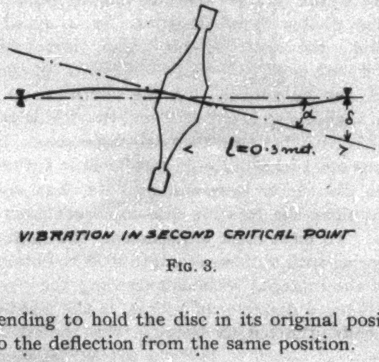
Flexible shaft. At a speed of 20,000 rev. per min., it would not be practical to use a rigid shaft as in ordinary machines. It was therefore necessary to adopt the principle employed in the deLaval steam turbine, that of a flexible shaft which allows the disc to revolve round its exact mass center, thus avoiding any strain on the bearings due to centrifugal force. In a turbine of this type designed for a speed of 20,000 rev. per min., the shaft is very thin, about the size of a lead pencil, but not very long. A shaft of such proportions would not be suitable for the alternator in which the exactness of the air-gap is essential and the disc is subject to the magnetic attraction between field and armature. The shaft of the alternator must have not only considerable stiffness, in order to keep the disc in an accurate position, but also sufficient flexibility to allow the rotating disc to adjust itself to its own mass center. To meet these requirements the shaft is designed like a stiff spring with uniform strength so as to obtain maximum work out of the material without exceeding the elastic limit in any part. It has a diameter of 1.25 in. in the middle and 0.625 in. at the ends, the length between the centers of bearings being 28 in.

When the machine is brought up to speed, severe vibration occurs at two distinct critical speeds, one at 1700 rev. per min. and the other at 9000 rev. per min. The vibration increases gradually when the machine approaches the critical speeds. When the vibration has reached its maximum, it ceases suddenly and the machine runs smoothly and with surprisingly little noise, indicating that the disc has fallen into step with itself, so to speak, and is rotating around its own mass-center. The critical speed, which can be predetermined approximately from the design of the shaft and the disc, occurs when the natural vibration of the shaft with the disc coincides with the revolutional speed.

The first point of resonance is the one at which the shaft vibrates like a string, as shown in Fig. 3. The spring force of



VIBRATION IN FIRST CRITICAL POINT



VIBRATION IN SECOND CRITICAL POINT

FIG. 3.

the shaft tending to hold the disc in its original position is proportional to the deflection from the same position.

Let the deflection $= \delta$
The spring force $= P$
Hence $P = k\,\delta$

in which k is a constant corresponding to the stiffness of the shaft. The constant k can be determined by calculating the deflection of the shaft from its dimensions. The result of such a calculation gives $\delta = 0.0024\ P$ cm. or 0.000024 meters. in which

P is expressed in kilograms. The weight of the disc is 13.6 kg. and the mass $= m = \frac{13.6}{9.8}$.

The equation for resonance in the first critical point is derived by assuming that the shaft swings as a string with a weight in the middle. In order to define the condition for resonance, it is assumed that the disc is brought out of center by an arbitrary amount δ. The condition for mechanical resonance occurs if the centrifugal force of the mass of the disc rotating at a radius δ is equal to the centripetal force created by the deflection of the shaft to the amount δ from its normal shape.

Centrifugal force $= m\,\delta\,\omega^2$

Where ω is the angular velocity.

The spring force of the shaft has been designated P

$$m\,\delta\,\omega^2 = P = \frac{\delta}{0.000024}$$

and introducing $m = \frac{13.6}{9.8}$

$$\frac{13.6}{9.8}\,\delta\,\omega^2 = \frac{\delta}{0.000024}$$

$$\omega^2 = \frac{9.8}{13.6 \times 0.000024}$$

$$\omega = 173$$

Rev. per sec. $\frac{\omega}{2\pi} = 27.5$.

Rev. per min. 1650.

The second harmonic is the one at which the disc vibrates around an axis vertical to the shaft and the shaft assumes an S shape. The momentum exerted by the spring force on the disc is proportional to the angular deviation of the disc.

The relation is $P\,l = k\,\alpha$.

The constant k can be derived from the dimensions of the shaft. In this case

$$k = \frac{l^2}{0.000024} = \frac{0.3^2}{0.000024} = 3750$$

The inertia of the disc for rotation around an axis vertical to the shaft may be designated I. In this case

$I = 0.0052$ expressed in meters and kilograms.

The equation for mechanical resonance is

$$I \alpha \omega^2 = P l$$

in which ω is the angular velocity.

Substitute $P l = k \alpha = 3750 \alpha$

$$I \alpha \omega^2 = 3750 \alpha$$

$$\omega^2 = \frac{3750}{0.0052}$$

$$\omega = 850$$

$$\text{Rev. per sec.} = \frac{850}{2 \pi} = 136$$

Rev. per min. = 8200.

A number of mechanical features which have been the principal problems in the development of this machine are described in the following.

Method of drive. The first machine built was belt-driven. After a good deal of experimenting with different kinds of belts and pulleys, it was found feasible to run the machine at 15,000 rev. per min., corresponding to 75,000 cycles. However, it also became apparent that this method of driving could not be accepted for practical use, so that the later machines have been equipped with gears. Although these gears are designed for reduction of speed, they appear to work satisfactorily when the action is reversed. The gear ratio is 10 to 1.

Revolving disc. The disc is designed so as to have uniform stresses in all parts and consequently the greatest possible margin of safety. The disc is made of chrome-nickel steel with an elastic limit of about 200,000 lb. per sq. in. At a frequency of 100,000 cycles the speed is 20,000 revs. per min. The diameter of the disc being one foot, the peripheral speed is 1,000 feet per second or 700 miles per hr.; in other words, the disc would roll over to Europe in 4 hr. The centrifugal force of the material in the edge of the disc is 68,000 times its own weight, but owing to the shape of the disc, which is designed for maximum strength, the stresses are only 30,000 lb. per sq. in., giving a factor of safety of 6.7 to 1.

Heating and air friction. If it be born in mind that the disc has 300 teeth on each side spaced at a distance of 0.125 in. and that these teeth pass the face of the stationary armature at a rate of 1000 ft. per sec. with a clearance of 0.015 in., it can be readily understood that the air friction in the gap must be considerable. It was found that the machine heated up excessively owing to air friction, but this has been overcome by filling the slots with non-magnetic metal so that the disc offers a perfectly smooth surface. Then another difficulty was encountered owing to centrifugal force acting on the fillers, each of which is subject to a centrifugal pull of 80 lb. During some of the first attempts, when the slots were simply filled with hard solder, it happened that some of the fillers broke loose. It was interesting to notice that an unbalancing centrifugal force of 80 lb., which would have been enough to bend the shaft at standstill, did not affect the machine, which, in every case, continued to run as if nothing had happened. In the final construction, in which the fillers are anchored so as to stand the strain, they consist of U-shaped phosphor-bronze wires supported directly by the steel teeth so that the solder is needed only to fill the joints.

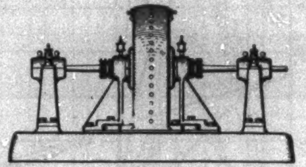
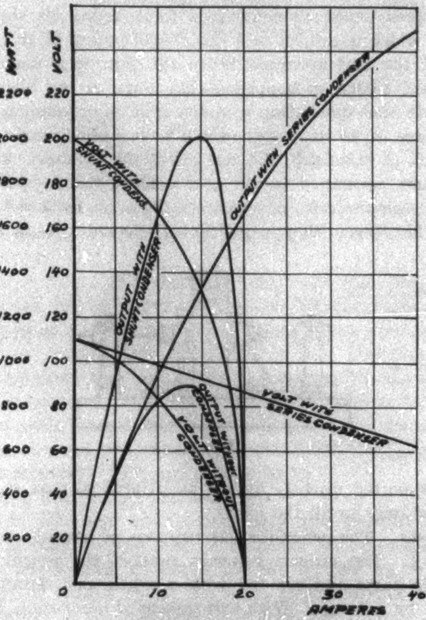


Fig. 4.

Bearings. The generator has two sets of bearings as shown in Fig. 4. The outside bearings support the weight of the revolving parts and are fed with a continuous stream of oil supplied by a pump. With this system of lubrication, the machine can run continuously at full speed with a temperature rise of the bearings of only 5 degrees above the temperature of the oil in the tanks. The necessity of the continuous oil feed is demonstrated by the fact that the temperature of the oil in the tank reaches 20 degrees above the surrounding air.

One of the functions of the middle bearings is to prevent excessive vibrations when the shaft passes the speeds of mechanical resonance. During normal operation, the shaft does not touch the middle bearings, which are bored out to give 1/64 in. clearance; at the critical speed, however, the shaft touches the bearings.

The end-thrust of the shaft is taken up partly on the middle bearings and partly on the end bearings. If the air gaps on both sides of the disc were not equal, the magnetic end thrust might be considerable, but with this arrangement of divided end thrust the adjustment seems to be to a certain extent automatic. If the disc has a tendency to move over to one side due to a difference in size of the air-gaps, the corresponding middle bearing will heat up and the same side of the shaft will expand longitudinally, thereby relieving the middle bearing as well as correcting the air-gap.



REGULATION CURVES
2KW 100000 CYCLE ALTERNATOR

FIG. 5.

Electrical characteristics. A generator of this kind is always used in connection with a capacity, which is located either in the aerial, as in the case of wireless telegraphy, or in a condenser of suitable capacity used in order to obtain the proper tuning. The best method of showing the characteristics of the generator, without reference to any certain application, is to assume the load to be non-inductive and use a condenser of a fixed capacity as an attribute to the generator. The most typical performance of the generator operating in conjunction with a condenser is the one in which the condenser has an impedance equal to the inductive impedance in the generator winding and is connected in series with the generator. This combination gives the generator a maximum output for any load. A condenser arranged in this way considerably increases the useful performance of the generator and should be regarded as a part of the generating outfit. The tests of the alternator

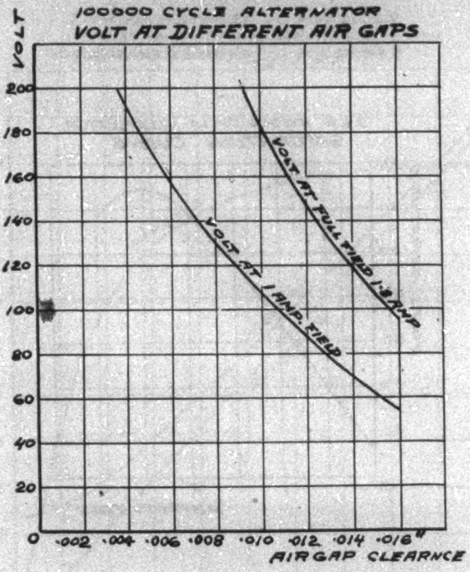


FIG. 6.

described here show that the reactance of the armature winding is 5.4 ohms at 100,000 cycles. The condenser which ought to be used in connection with the machine at the same frequency should have the same impedance expressed in ohms. If the capacity is expressed as usual in microfarads, it should be

$$C = \frac{1}{5.4 \times 2\pi \times 100{,}000} \text{ farads}$$

$$= \frac{10}{5.4 \times 2\pi} = 0.3 \text{ microfarads}$$

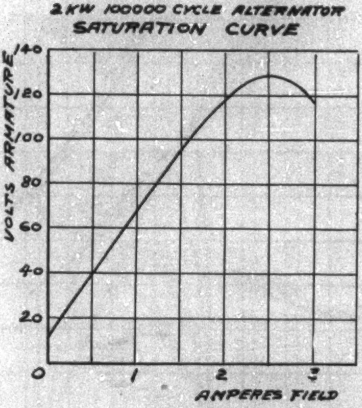


Fig. 7.

Regulation curves of the alternator are shown in Fig. 5. From this diagram it appears that the combination of alternator and series condenser gives the same terminal voltage at any load as would a generator which had the same electromotive force and the same ohmic resistance but no inductive drop. In other words, the condenser completely offsets the reactance of the winding, and the regulation is determined entirely by the ohmic resistance.

Tests, as well as practical use of these machines for wireless telegraph work, have shown that the commercial output of the alternator is limited by heating of the armature winding. In building these alternators for practical purposes, the need for a commercial rating of the machines has already been realized. The basis for rating which has been adopted for these machines

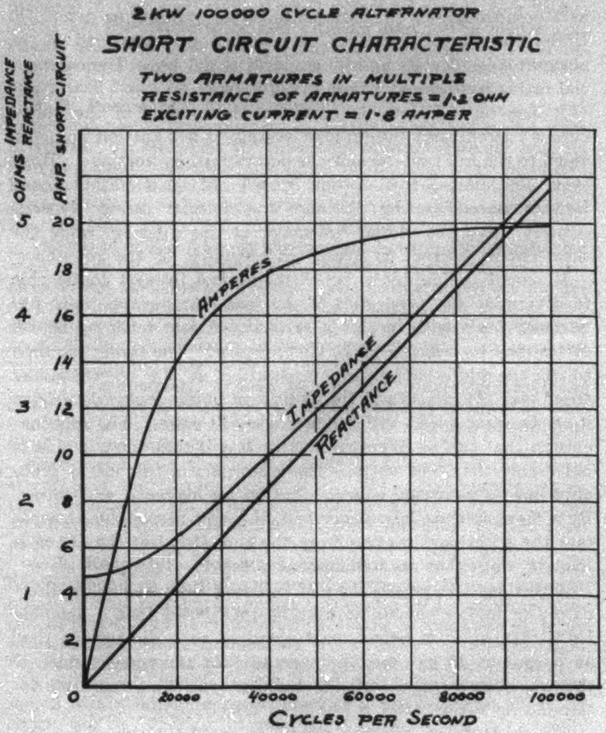


FIG. 8.

is illustrated by the rating of the 2-kw., 100,000-cycle alternator.

The characteristics of the machine as given by test are the following:

No load voltage, 110.

Ohmic resistance, 1.2.

Short-circuit current, 20 amperes.

Continuous capacity at 45 degrees rise, 30 amperes.

From the above data, it is apparent that the alternator cannot be operated up to its full thermal capacity without a condenser, and in selecting a condenser the capacity is regulated so as to compensate for the inductance of the winding as described. Under these conditions, the maximum continuous load of the alternator is 70 volts and 30 amperes or 2.1 kw. The commercial rating has therefore been made 2 kw.

It may be of interest to note that the product of the short-circuit current and the no-load voltage is 2.2 kilovolt-amperes, equal to the full load-capacity as determined by heating . However, the short-circuit current would not be a suitable basis for commercial rating; because the thermal rating depends entirely upon the ohmic resistance of the winding, while the short-circuit current is nearly independent of the resistance.

It would undoubtedly be of theoretical interest to be able to determine the properties of the iron core at the high frequencies dealt with in this generator. A test made at 60,000 cycles may be referred to for this purpose. The power required to run the whole set without excitation at the corresponding speed was 1340 watts and the additional power required to drive it at the same speed with full field was 330 watts. The only conclusion that can be drawn from this test is that the core loss is not higher than 330 watts. The main part of this loss is probably due to increased bearing friction by magnetic end thrust. By a more delicate laboratory test, it might be possible to separate the additional friction from the core loss, but the above is the only data that are available at present.

Regarding the possibilities of building high-frequency alternators of higher output, it may be mentioned that a machine for 50,000 cycles is being constructed of such dimensions that an output of 35 kw. can be expected. At the present state of the art, however, it is safer to build the machine first and determine its rating after it has been tested.

The question of whether machines can be designed for frequencies still higher than 100,000 cycles cannot be decided offhand. Considering, however, that the present generator has a large margin in the mechanical strength of the revolving disc as well as in the length of the air-gap, etc., it appears probable that still higher frequencies can be reached by direct generation with revolving machinery.

DISCUSSION ON "ALTERNATOR FOR ONE HUNDRED THOUSAND CYCLES." FRONTENAC, N. Y., JUNE 28, 1909

John B. Taylor: I wish to ask why, in Fig. 7, the voltage falls off with increasing field excitation?

J. C. Lincoln. I wish to ask why, in the design of a small machine of this sort, such a small diameter as one foot is selected for the diameter of the rotating part. The centrifugal strains would be less with a given peripheral speed if the revolving part were made 2 ft. or 18 in. in diameter. Also, larger pole space on the periphery would be obtained.

D. B. Rushmore. At one time the induction alternator was in general use in this country, especially when 133 cycles were in vogue. At 60 cycles the induction alternator easily held its own as a small high-speed machine, but became more expensive for other frequencies, and at 25 cycles could not compare with other machines. However, where high frequencies are desired it is necessary to use this form of machine.

The curve in Fig. 5 shows the increased output of the machine with the shunt condenser under somewhat the same conditions as exist in a transmission system. The critical speed is a matter of great interest and importance in many of the lines of mechanical work where, because of the type of prime mover, or to obtain higher efficiency at lower cost, the tendency is to use velocities limited only by the strength of material.

C. J. Fechheimer: I wish to ask Mr. Alexanderson if the critical speed is affected by the means of support with the flexible shaft used in this alternator; that is, will self-aligning or fixed bearings materially affect the critical speed?

I also wish to ask if careful tests were made of the tensile strength of the chrome-nickel steel. Mr. Alexanderson states that the elastic limit of the steel used is about 200,000 lb. per sq. in., whereas the chrome-nickel steel furnished by the steel mills has an elastic limit of about 110,000 lb. per sq. in.

A. E. Kennelly: It is interesting that a condenser should be considered as normally attached to the machine in order to obtain normal output; although this would be a dangerous precedent if it should be considered necessary in machines of larger proportions or lower frequencies, since rotary condensers might become necessary as part of the equipment of the machine.

I wish to ask Mr. Alexanderson whether he has made measurements of any kind, to show whether a physiological effect, or shock, can be felt from the machine at 100,000 cycles per second? We know that at the frequency of 2000 cycles per second a shock can be felt and that there is a certain high frequency at which a shock is not felt.

E. F. W. Alexanderson: Answering the question asked by Mr. Taylor: why the voltage of the generators decreased with increased field strength. The decrease of voltage is due to the nature of the inductor-alternator. The profile of the disc looked at from the end is indicated in Fig. 1, showing one wire in each slot of the armature. The variation of field strength in the separate armature coils is produced by the varying air-gap when a tooth is opposite or when a gap is opposite to a coil. If the excitation is driven too high, the teeth saturate and the difference between maximum and minimum induction becomes less. That is the reason why a certain field excitation gives the maximum voltage.

It is, without doubt, true that a larger diameter would materially increase the capacity. A 1-ft. diameter was selected because in building the experimental machine the item of cost had to be considered. The machine now building, which is expected to have an output of 35 kw., is designed with a diameter of 3 ft.

The resonance of the shaft, so far as I have been able to observe, has nothing to do with the alignment of the bearings. The bearings are self-aligning. Whether it would be different with a non-lined bearing, I could not tell.

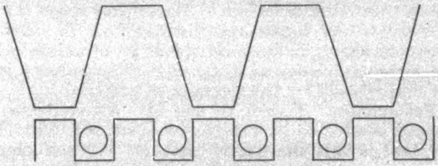


FIG. 1.

In making the disc in the lathe and in the milling machine, the opinion of those who worked on it is that it is an extremely tough material. It has, therefore, been, attempted and will probably work out successfully, to have the material cut before it has been tempered, because the high tensile strength of 200,000 lb. per sq. in. is not inherent in the material until it has been tempered by a special process. It is hoped it can be treated without changing the shape. The same process has been used generally in automobile gears.

Dr. Kennelly asked if it were possible to feel a 100,000-cycle shock. I can assure him that it is. I could not feel any difference between alternating current at 100,000 cycles and direct current. 100 to 150 volt, at the high frequency gives the same sensation as a direct current of the same voltage.

In developing the 100,000-cycle generator one practical point was discovered which may be of interest in regard to the discussion of Dr. Kennelly's paper, as to the radiation from wires. The wire placed in the slot has a diameter of 0.016 in. It has a triple silk covering and coating of varnish. One of these wires, when placed in the slot, carries 15 amperes at a rise of 25 degrees centigrade; that is, twice as much as it will carry in the open air. Naturally the iron, which is closely in touch with the coil, takes off more heat than the air. The measurements are made by resistance, and the rise of temperature of the wire takes only a few seconds. The current density in it is about 75,000 amperes per square inch, against 2000 to 3000 in the ordinary machine.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

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METHOD OF TESTING TRANSFORMER CORE LOSSES, GIVING SINE-WAVE RESULTS ON COMMERCIAL CIRCUITS

BY L. W. CHUBB

It is well known that if the wave-shape or the frequency varies from the normal, the loss in a transformer core at normal voltage varies also. It is obvious, however, that the normal loss, that is, the loss with the sine-wave shape and the normal frequency of, say, 60 cycles, can be obtained under the abnormal conditions of wave-shape and frequency by either raising or lowering the voltage. What is needed, then, is an indicator which will enable the voltage to be so adjusted that the loss in a transfomer core as measured upon an ordinary wattmeter will be the same as it would be at normal voltage on a circuit having a sine-wave shape of normal frequency.

Suppose such an instrument or indicator were so made that when connected to an alternating-current circuit, it would indicate the effective value of a sine-wave voltage of a certain normal frequency, such as 60 cycles, which would cause the same watt loss in a transformer core as the circuit to which it is connected. For core-loss tests it would be necessary simply to adjust the voltage of the circuit so that the special instrument would indicate the normal voltage, say, 110 volts, although an ordinary voltmeter might read several volts higher or lower, and take a wattmeter reading of the input to the transformer under test. This reading then would be the same as would be found if the measurement were made at 110 volts on a 60-cycle circuit having a sine wave of voltage. Such an instrument, termed an iron-loss voltmeter, is described in this paper, which takes up in some detail the practical importance of the subject of transformer core-loss tests, the nature and magnitude of errors, and the methods proposed for correcting them.

To the central-station operator or user of distributing or power transformers, the iron loss of his transformer is of the greatest importance. But of all tests on electrical apparatus one of the most difficult to check and agree upon is the measurement of the core loss of a shunt transformer. Reports of tests for the same transformer taken at different times or in different places will seldom agree within three or four per cent, and often differ as much as ten per cent. The difference is sometimes due to an actual change in the transformer, such as aging of the iron core or a change in the mechanical make-up, or physical stresses of the core due to extreme temperature changes or vibrations during transportation.

Changes in testing conditions and errors of testing methods, however, are more often responsible for the differences and errors in core-loss results. Frequency, temperature and wave-shape variations; wattmeters which are inaccurate on low power-factor tests; voltage control by inductance and resistance; connecting voltmeter and wattmeter pressure leads on the line side of the wattmeter; and paralleling windings which are of wrong ratio, are all frequent sources of error. Of all these the wave-shape difficulties are the most serious, are almost always present, and have been the most difficult for which to make corrections in the usual commercial tests.

The voltage wave-shapes of alternating-current circuits differ greatly. The difference or variation from the sine may be inherent in the alternator, or distortions may be caused by abnormal conditions of load and voltage drops in the circuits. Such voltage distortions are generally caused by having high inductance and resistance in the circuit such as the alternator armature, the coils of measuring instruments, and the rheostats and choke coils which are often used to regulate the voltage. A peaked wave of voltage will cause a lower core loss, and a flat wave a higher loss than a sine wave of the same effective voltage.

On account of this variation with wave-shape, it is desirable that the core-loss tests and data for transformers be expressed in terms of some certain wave-shape, as well as frequency and voltage. Guarantees of core losses are generally based on a sine wave, but we sometimes find them stated in terms of an "average commercial wave." The wave-shapes of commercial circuits may vary between wide limits, and in the majority of cases will be found to be peaked, especially at the terminals of a transformer under test.

The Standardization Rules for a sine wave allow a deviation from the equivalent sine of ten per cent of the maximum ordinate of the equivalent sine wave. If instead of a true sine wave, this nominal sine is to be used as a basis for core-loss guarantees, the conditions of test and results obtained will still be indefinite. Figs. 1 and 2 show two waves which meet sine-wave specifications, but a transformer tested for core loss on them will differ from 7.8 per cent below to 5.8 per cent above the loss which would be obtained on the equivalent sine. These are, of course, theoretical waves, but they show the limit of core-loss error for an average transformer, caused by waves which meet sine-wave specifications.

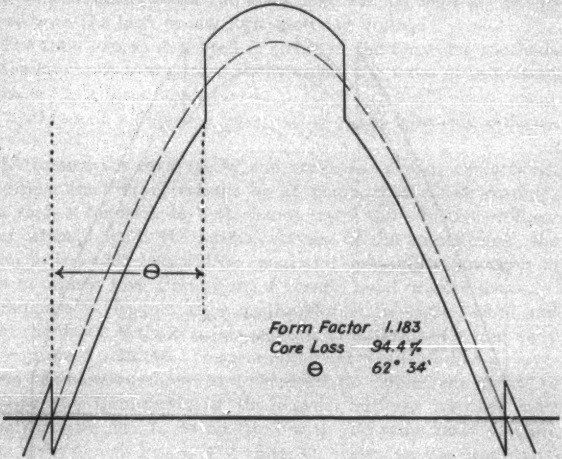


Fig. 1.

On account of the accuracy required for core-loss tests, the difficulty of obtaining a good sine wave for test, and the difficulty of correcting results to a sine value by the methods which are now in vogue, it seems very desirable that a method of test be available which will remove the wave-shape difficulty.

It is the purpose of this paper to present a method of testing which will give sine-wave values of transformer core losses on very distorted testing waves, without the aid of an oscillograph, contactor, synchronous commutator, or even exact knowledge of the wave-form or frequency of the circuit.

The iron loss of a transformer consists of the eddy-current loss and the hysteresis loss which are present in about the same relative proportions in transformers designed for the same frequency. The eddy-current loss in a given transformer is dependent upon the root mean square of the instantaneous values of the induced voltage, while the hysteresis loss is dependent upon the maximum magnetic induction in the iron, which in turn is dependent upon the average of the instantaneous values of the induced or counter voltage. This dependence of eddy loss upon root-mean-square volts and of hysteresis upon average volts, is practically independent of wave-shape variation, except in cases when the voltage curve passes through zero more than twice per cycle; or the flux distribution is varied; or the impedance to high-frequency components of the eddy loss varies greatly

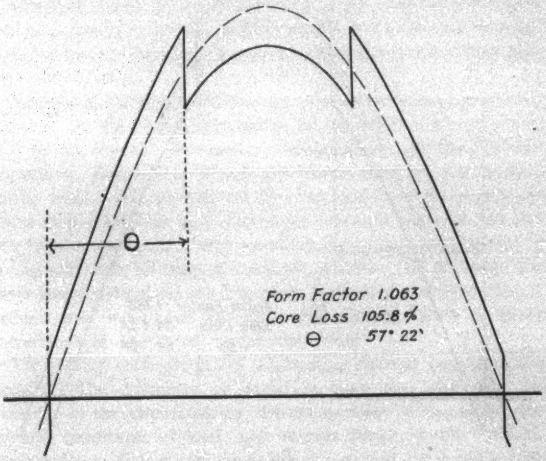


Fig. 2.

It is obvious that if the usual alternating-current voltmeter is used to adjust voltage in core-loss tests and the wave-shape of voltage is not a sine, then the eddy loss in the transformer will be correct; that is, the sine value and the hysteresis loss will be low or high, depending upon whether the form-factor of voltage is respectively above or below 1.11. If the average voltage reading, taken from a voltmeter indicating the average, not the root-mean-square, voltage, or a synchronous rectifying commutator is used for the adjustment of voltage, the hysteresis loss will be correct and the eddy loss will be high or low to agree with the high or low form-factor of voltage.

The total loss as measured in either of the foregoing methods is therefore not a sine-wave result unless the wave of impressed voltage has a form-factor of 1.11. To obtain a sine-wave result of total loss on a distorted wave, either of the following is necessary:

Determine the form-factor and make the proper corrections.

Adjust the testing voltage by an instrument whose readings are such a function of both the average and effective voltage that when it reads the normal voltage of the transformer, the error in the eddy loss will be equal and opposite to the error in the hysteresis loss, thus giving a correct total or core loss.

Suppose a 110-volt, 60-cycle transformer is to be tested and that the result of the core loss is required in terms of a sine wave of impressed voltage. The testing circuit available has a wave-form of unknown shape, and there are no convenient means of finding the form-factor of the wave. Suppose another very small transformer to be on hand with the same ratio of eddy loss to hysteresis loss at 110 volts, 60 cycles, as the first transformer, the sine-wave core loss of the second transformer being 20 watts at 110 volts, 60 cycles. This small transformer and a wattmeter may be used in determining the proper voltage at which to test the unknown core loss in the larger transformer, on the given circuit. The voltage of the circuit should be adjusted until the energy input to the small transformer core is 20 watts, as indicated by the wattmeter. The core loss in the larger transformer is then read on a separate wattmeter, and the value thus obtained will be the same as would be measured at 110 volts on a 60-cycle sine wave of voltage. The above contains the essential elements of a method which will give sine-wave results of shunt-transformer core losses on any commercial alternating-current circuit.

The scheme is practically carried out by the use of a portable direct-reading instrument, known as an iron-loss voltmeter. This instrument indicates the effective or root-mean-square value of a sine wave of voltage which would cause the same iron loss in a transformer as the wave of voltage to which the instrument is connected will cause in the same transformer.

The iron-loss voltmeter consists essentially of a ring or core of laminated steel excited by a winding, and a wattmeter of suitable design on which to read the power input to the ring and all copper circuits in the instrument. The core and meter are mounted in suitable wooden cases, the instrument appearing as in Fig. 3. All connections are made inside of the instrument so that there are but two terminal posts to which the line is connected, as is the case in standard alternating-current voltmeters. Fig. 4 shows the arrangement of the circuits in the meter.

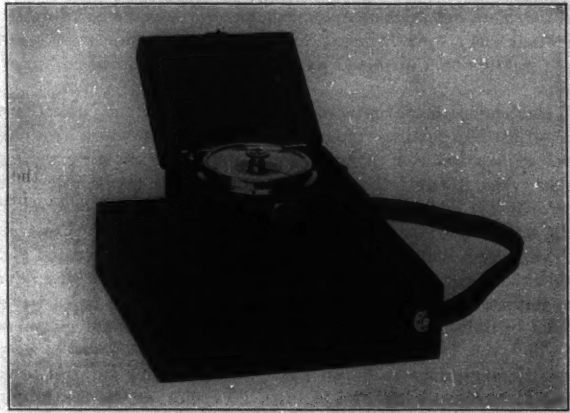


FIG. 3.

On the laminated core C is placed a winding W, the core member and winding being securely mounted in the lower case, and the two leads of the winding brought through the top and into the instrument case, which contains the meter movement.

A stationary current coil S is connected in series with the winding W and the terminals P P. The shunt circuit consists of the moving coil M, the non-inductive resistance R, and the compensating or adding coil C C, which is wound parallel to the series coil and of an equal number of turns. It can be readily seen that the deflection of the wattmeter movement will be caused by the total input to the instrument. This input is the hysteresis and eddy loss in the ring or magnetic rheostat, and the $I^2 R$ losses in all copper circuits of the instrument.

Of these losses the hysteresis in the magnetic rheostat is dependent upon the average value of the terminal voltage, and the eddy-current loss in the rheostat and the copper losses in the shunt circuit are dependent upon the effective value of the terminal voltage. The loss in the series circuit is a complex function of both the average and effective voltage, being proportional to the square of the exciting current of the ring. This series copper loss is so small that the exact law of its dependence on wave-shape is of no importance. The relative proportion of these component losses in the instrument is of importance.

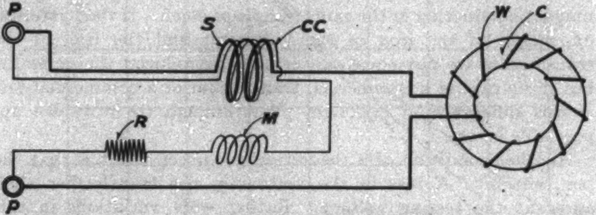


FIG. 4.—Internal connections of iron-loss voltmeter.

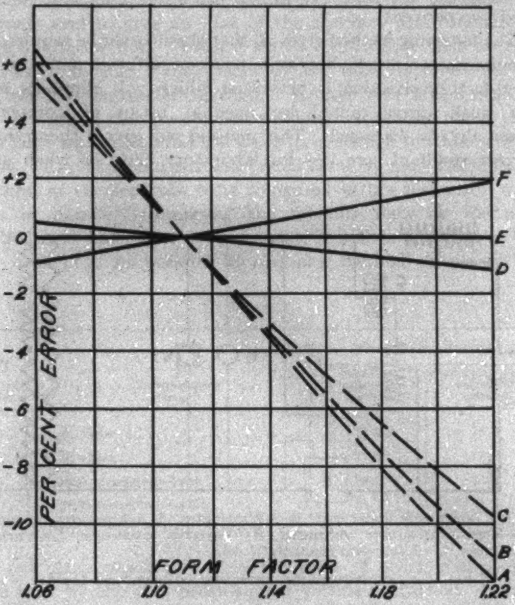
Before calibrating the instrument for a certain frequency, the adjustment of the ratio of eddy loss in the ring plus shunt copper loss, to the total loss, is made by changing the non-inductive resistance in the shunt circuit and the turns on the ring. This ratio of $I^2 R$ losses to total loss is made to be 20 per cent at about six-tenths of full scale voltage. After this adjustment is made, the instrument is calibrated in parallel with an alternating-current voltmeter on the pure sine-voltage wave of the required frequency from a small smooth-core alternator. The scale is drawn in to agree with the alternating-current instrument.

The iron-loss voltmeter, constructed and calibrated as described, may be used as a portable voltmeter in testing transformer core losses on any reasonably distorted wave of voltage. The test may be conducted without any knowledge of the wave-form. The voltage may be regulated through a considerable range by the aid of resistance or inductance, thus dispensing with the usual multi-voltage transformer or means of varying the field current of the alternator. The frequency need only approximate the normal value; and the final result of core loss as measured on a wattmeter will be the value which would be obtained on a sine wave of voltage at the normal frequency and voltage of the transformer.

By the Steinmetz formula the hysteresis loss in iron at constant frequency varies practically as the 1.6 power of the induction. This approximate exponent of 1.6 differs somewhat for different samples of sheet steel and it varies with changes of magnetic induction in the same sample of steel. If the hysteresis exponents of the iron in the voltmeter and the iron of the transformer are not equal, an error is introduced theoretically, but in no case of a commercial transformer or a commercial test is this difference of exponent great enough to introduce appreciable errors.

Another condition of a theoretically correct result is that the per cent of $I^2 R$ loss in the voltmeter and transformer shall agree at the testing voltage. Rather wide variations in this relation will, however, introduce errors which are very small in comparison to those obtained by using a root-mean-square voltmeter. No error is present on a sine wave, no matter what the relation of eddy and hysteresis may be in the transformer and instrument. When the wave-form is distorted the usual method of testing will introduce large errors and the iron-loss voltmeter method will be correct or introduce comparatively small errors. The curves of Fig. 5 show the per cent error that would be obtained when testing transformers of varying per cent eddy loss by the use of the root-mean-square voltmeter and an iron-loss voltmeter having 20 per cent eddy loss at the point of test.

Curves *A*, *B* and *C* show the errors which would be obtained by using the root-mean-square voltmeter in testing three transformers with 14 per cent, 20 per cent and 30 per cent eddy loss respectively on wave-shapes which have form-factors ranging from 1.06 to 1.22. Curves *D*, *E* and *F* show the corresponding errors which would be obtained on the three transformers when using the iron-loss voltmeter. Notice that the transformer with 20 per cent eddy loss can be tested without error on any wave-form by the new method, because the instrument assumed

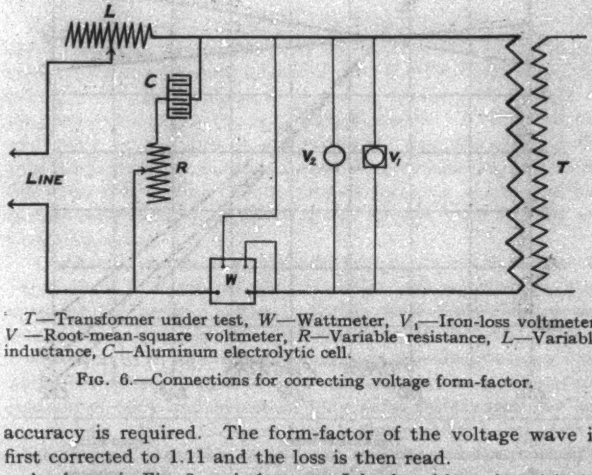


Curve	Transformer with	Tested with
A	14% eddy loss	R.m.s. voltmete
B	20% " "	R.m.s. "
C	30% " "	R.m.s.
D	14% " "	Iron "
E	20% " "	Iron "
F	30% " "	Iron

Fig. 5.—Curves showing effect of ratio of eddy and hysteresis loss on core loss tests by the two methods.

has 20 per cent copper loss. Sixty-cycle transformers of commercial design will be found to have about 14 per cent to 30 per cent eddy-current loss and to average about 20 per cent eddy loss at normal voltage. Curve *B* then shows the usual errors by the old method. The errors by the new method will seldom be more than one per cent and, even with the worst proportions of eddy and hysteresis loss and worst wave-shapes, will not exceed two per cent.

The foregoing method gives all that should ever be required for commercial accuracy, but as a point of interest a method of form-factor correction is presented which will eliminate even the small errors caused by unequal ratios of component losses already discussed. This method will give a theoretically correct result of core loss for laboratory tests or when great accuracy is required. The form-factor of the voltage wave is first corrected to 1.11 and the loss is then read.



T—Transformer under test, *W*—Wattmeter, V_1—Iron-loss voltmeter, *V* —Root-mean-square voltmeter, *R*—Variable resistance, *L*—Variable inductance, *C*—Aluminum electrolytic cell.

FIG. 6.—Connections for correcting voltage form-factor.

As shown in Fig. 6, an inductance *L* is placed in series with the line and an aluminum electrolytic cell *C* is connected across the line and between the inductance *L* and the wattmeter *W*. The inductance causes a peak in the wave, and the aluminum cell, which is working above its critical voltage, short-circuits or flattens out the peaks until the form-factor is 1.11. This correction or adjustment of form-factor is made by varying the resistance *R* and the inductance *L*. When the readings of the root-mean-square voltmeter and the iron-loss voltmeter agree, the form-factor is 1.11 and the core-loss reading is taken. This method does not necessarily give a sine wave for the test but it gives a wave having the same form-factor, and has been found to be very accurate.

Some specimen tests are shown herewith for the sake of clearness and to give an idea of the accuracy and commercial value of the method. Table I shows comparative tests on two 3000-kw., 60-cycle transformers by the usual method and by the iron-loss voltmeter method. Voltage was taken from a 115-volt tap in the low-tension winding. It will be noted that such large units distorted the wave-form enough to make serious errors. Each transformer was tested alone by each method and the sum of the separate tests compared with a test made with both in parallel. Assuming the separate tests by the new method and their sum to be correct, it will be noted that the test with both in parallel by the new method checks within 1.1 per cent, which is within the error of observation. Also note that by the root-mean-square voltmeter method, *A* alone gives a result 6.2 per cent low; *B* alone, 4.5 per cent low, and the parallel test does not agree with the sum of the separate tests and is over 11 per cent below the correct sine value.

TABLE I.

Test No.	Transformers tested	Core loss in kilowatts	
		Iron-loss voltmeter method	Root-mean-square voltmeter method
1	*A*, alone	17.7	16.6
2	*B*, alone	17.8	17.0
	Sum of separate tests	35.5	33.6
3	Both tested in parallel	35.1	31.5

Table 2 shows a similar comparative test on three smaller transformers, made with an alternator having a good sine wave at no load. The results of the last column show the errors of the root-mean-square voltmeter method under conditions, which were supposed to be very good. They also show how consistent the results of the new method are. Tests numbered 5 and 10 were made with some inductance in series with the line. It will be seen by the voltmeter readings of test 5 that the wave was quite distorted, and that the result by the new method was practically unaffected, while the result by the root-mean-square

TABLE II

IRON-LOSS VOLTMETER METHOD

No.	Transformer	Volts		Total watts	Instrument losses			Core loss (watts)
		Root mean square	Iron-loss meter		*VM+WM*	Iron loss *Vm*	Total	
1	*A*............	111.2	110.0	193.6	15.9	27.7	43.6	150.0
2	*B*............	111.2	110.0	189.9	15.9	27.7	43.6	146.3
3	*C*............	111.2	110.0	189.9	15.9	27.7	43.6	146.3
	Sum							442.6
4	*A, B, & C* tested in parallel	112.6	110.0	475.5	9.9	27.7	37.6	437.9
5*	*A, B & C* tested in parallel.....	122.3	110.0	478.0	11.7	27.7	39.4	438.6

ROOT-MEAN-SQUARE VOLTMETER METHOD

No.	Transformer	Root mean square	Iron-loss meter	Total watts	*VM+WM*	Iron loss *Vm*	Total	Core loss (watts)
6	*A*............	110.0		162.3	15.5		15.5	146.8
7	*B*............	110.0		158.3	15.5		15.5	142.8
8	*C*............	110.0		158.3	15.5		15.5	142.8
	Sum							432.4
9	*A, B & C* tested in parallel....	110.0		430.5	9.5		9.5	421.0
10*	*A, B & C* tested in parallel....	110.0		387.5	9.5		9.5	378.0

* Voltage wave purposely peaked with inductance.

TABLE III

IRON-LOSS VOLTMETER METHOD

No.	Volts		Core loss	Remarks
	Root-mean-square meter	Iron-loss meter		
1	118.5	110.0	185.2	Alternator #1 light load.......... Fig. 7
2	115.0	110.0	184.6	Alternator #1 loaded..................
3	115.5	110.0	185.6	Alternator #2 light load.......... Fig. 8
4	123.4	110.0	186.2	Alternator #2 loaded............. Fig. 9

ROOT-MEAN-SQUARE VOLTMETER METHOD

No.	Root-mean-square meter	Iron-loss meter	Core loss	Remarks
5	110.0		165.1	Alternator #1 light load.......... Fig. 7
6	110.0		171.1	Alternator #1 loaded..................
7	110.0		170.4	Alternator #2 light load.......... Fig. 8
8	110.0		157.7	Alternator #2 loaded............. Fig. 9

method was lowered an additional 10 per cent. The additional columns show the intermediate steps used to work out the core loss from the observed readings of volts and total watts input. The wattmeter had no compensating coil to correct for its shunt power and, since the voltmeter and pressure leads of the wattmeter were connected to the terminals of the transformer, corrections had to be made for the instrument loss of the voltmeter and the shunt circuit of the wattmeter. The loss in the iron-loss voltmeter is known from a calibration curve to be 27.7 watts when the instrument reads 110 volts, but to correct for the shunt power in the wattmeter we must use the formula $\frac{E^2}{R}$, where E is the root-mean-square voltage. This makes it clear why the root-mean-square voltmeter reading is also taken.

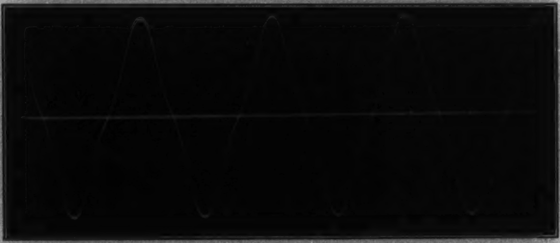


FIG. 7.

In this table also it may be seen that the sum of the separate tests by the root-mean-square voltmeter method does not check with the sum as tested in parallel, and that the errors of the tests by this method are from 2.1 per cent to 13.8 per cent low.

Table 3 shows some tests made on two different alternators at light load and during heavy low-power-factor load. Both the alternators in these tests have a peaked wave on no load. Alternator No. 1 is a large, and No. 2 is a small, machine.

Oscillograms of Figs. 7, 8, and 9 show the voltage wave at the terminals of the transformer under the different conditions of test in Table 3. This table shows the results by the new method to agree within less than nine-tenths of one per cent, while the results by the root-mean-square voltmeter method are from 7.7 per cent to 14.9 per cent low and differ among themselves over 8 per cent.

Table 4 shows the effect of errors of frequency on the core losses measured by the two methods. The results of core-loss tests by the new method are practically independent of frequency errors in testing voltage. This means that the core loss at normal frequency and sine voltage can be obtained on a circuit with both frequency and wave-shape errors. It also means that transformer core losses, on a distributing line where the wave-shape is distorted and the frequency unknown, can be tested about as accurately as in a laboratory or at the source of power where the frequency can be accurately adjusted and the voltage wave-shape kept constant by adjusting voltage with the alternator field or a multi-tap transformer.

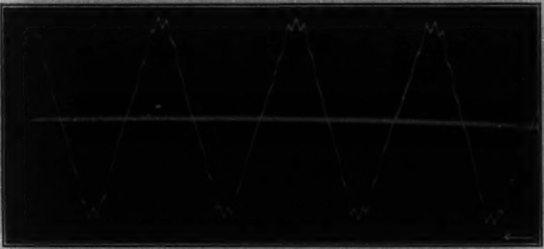


FIG. 8

FIG. 9.

The tests of Table 4 were made on an alternator with good wave-form, the voltage being adjusted by means of an auto-transformer. The conditions of wave-shape voltage were supposed to be very good and yet it will be noted that the error at 60 cycles by the root-mean-square voltmeter method is as great, owing to wave-form distortions, as the error at 53 cycles by the method.

In closing, it is only fair to speak of the disadvantages of the iron-loss voltmeter and the new method of test. The instrument is necessarily heavier than the ordinary alternating-current voltmeter. The internal losses of the instrument are high and in testing very small transformers the correction for instrument losses is as large as the core loss of the transformer. For high-voltage tests the usual voltage transformer cannot be used on account of the relatively large current taken by the instrument and its poor power-factor. A voltage transformer to be used with the iron-loss voltmeter must be especially designed with heavier copper and low reactance. The instrument can be made direct reading for only one frequency, and, when used on other frequencies, must be used with a calibration curve. These disadvantages are not of great importance as there are generally low-voltage taps on high-voltage transformers, to which the meter can be connected, and there are but few standard frequencies in terms of which tests will be required.

TABLE IV

Iron-loss voltmeter method				Root-mean-square voltmeter method			
Frequency		Core loss		Frequency		Core loss	
Cycles	% error	Watts	% error	Cycles	% error	Watts	% error
68.1	+13.5	201.1	+1.6				
66.4	+10.7	201.0	+1.5	67.1	+11.8	183.1	-7.5
64.5	+7.5	199.3	+0.7	63.3	+5.5	188.9	-4.6
63.7	+6.2	199.5	+0.8	62.1	+3.5	191.6	-3.2
60.0	Normal	198.0	0.0	60.0	Normal	195.6	1.2
59.5	-0.8	197.8	-0.1	57.0	-5.0	202.7	+2.4
59.0	-1.7	197.7	-0.2	54.2	-10.0	208.7	+5.4
56.8	-5.3	196.8	-0.6	52.3	-12.8	211.3	+6.7
55.2	-8.0	197.1	-0.5	50.5	-15.8	218.6	+10.4
53.0	-11.7	195.8	-1.1				
50.5	-15.8	195.1	-1.5				

DISCUSSION ON "METHOD OF TESTING TRANSFORMER CORE LOSSES GIVING SINE-WAVE RESULTS ON COMMERCIAL CIRCUITS." FRONTENAC, N. Y., JUNE 28, 1909

Frederick Bedell: The author is to be thanked for perfecting as an instrument that which, no doubt, more than one of us has already used as a method. We have used a calibrated transformer, whose losses under certain conditions have been accurately determined, for comparison with the transformer under test. Mr. Chubb's instrument will certainly prove most valuable if its calibration can be depended upon. Where one has a testing laboratory at his disposal he can readily check up such an instrument from time to time. When, however, one is remote from such testing facilities and has used an instrument of this kind for a number of years, a question arises as to whether it can be depended upon and will not be affected by time and temperature. I should like to hear from the author in regard to this.

Charles P. Steinmetz: In Mr. Chubb's paper a definition is given for the form-factor which I consider rather unfortunate. It is as follows: the ratio of the effective to the mean value. In this sense this term is frequently used, but it gives to the sine-wave a value of 1.11. Since in all electrical engineering we consider the sine-wave as the standard, it certainly is very unfortunate to define form-factor so that for the standard wave it does not give unity. Form-factor should be defined so as to give unity for the sine-wave. That is, *form-factor is the ratio of the effective to the mean value of the alternating wave, divided by the corresponding ratio of the sine-wave*. Hereby the sine-wave has form-factor 1, the form-factor of any other wave would directly represent the deviation from the standard wave, and the 1.6 power of the form-factor would be the correction factor of the hysteresis loss.

M. G. Lloyd: It seems to me that the instrument described ought to have a wide use, especially among smaller manufacturers and central stations where there are no facilities for getting sine-waves. I know of one case, for instance, which comes up in connection with some government work. The Navy Department in its permanent specifications for transformers at present requires the manufacturer who bids on its proposals to have the means of using and determining the sine-wave and control of the frequency. That prevents a great many of the smaller manufacturers from bidding on government contracts. An instrument like this would enable one to make tests without these facilities. If admitted by the Navy Department—I am told it is considering the use of such an instrument—it would be possible for a great many companies without testing facilities to participate in bids on such contracts. The difficulty of getting a sine-wave, as I have found by experience, is not at all small. In my paper on the "Testing of Transformer

Steel" I cite an instance of a generator which, to look at the oscillogram only, one would suppose gave a sine-wave. It had a very smooth and even curve and appeared to be perfect in all respects. An actual measurement, however, showed that the form-factor was considerably off. I take it to be a fact that it is not at all easy to get a machine that gives a form-factor sufficiently near to the sine-wave.

As regards the general use of these instruments, it is evident that the errors are only eliminated when the eddy currents bear a definite proportion to the hysteresis. Of course the errors in the instrument increase but slowly with variation of that ratio; but it occurs to me, in using it with widely different kinds of material, such as silicon-steel and the ordinary steel, that the same instrument perhaps could not be calibrated to read very well on both classes of material. While silicon-steel is in almost general use for certain classes of transformers, still, I understand, on low frequency many manufacturers still use the old variety of steel. Perhaps this is one thing that limits the use of the instrument.

As Mr. Chubb pointed out, I suppose the instrument could be supplied with different coils and calibrated to use on different frequencies, such as 25 and 60 cycles, which would make it of general application.

It seems unfortunate, too, that the instrument cannot be produced in a lighter form. Its excessive weight would hardly permit it to be classed with portable instruments, as it would not be convenient to carry such an instrument around.

L. T. Robinson: I wish to emphasize what Mr. Lloyd has just said about this instrument. It seems to me that it is a very good and very useful device, but is it not true that its application is limited to certain cases—to a line of transformers built, for instance, by certain designers for which they have prepared a suitable instrument? If such an instrument were trusted universally, would there not be found in commercial practice variations enough in the relation between eddy-current losses and hysteresis losses in transformers, and also variations enough in the form-factor of the waves, to make the results misleading?

Personally, I have used a method that amounts to about the same thing, but has not been worked up into combined instrument form. To a certain extent it is satisfactory but beyond that point it can not be trusted. I would prefer to see accurate work attempted in some other way; that is, by some instrument that would measure directly the form-factor based on which the correction would be applied to the transformer under test, either by separating the core loss of this transformer into its components or by using the somewhat definite knowledge that one would have of the constructive data.

Frederick Bedell: With reference to the definition of form-factor, I agree with Dr. Steinmetz that the present use is not the most logical. Form-factor as first used, following the lead of

Dr. Roessler in Germany, was defined as the ratio of the average to the effective value, which is the reciprocal of the value used in this paper. The form-factor of a square-topped wave is then unity, and of any other wave is less than unity, being 0.9 for a sine-wave. This is in conformity with efficiency and power-factor, which have maximum values of 100 or unity, and proceed from these values down to zero. For a number of years form-factor was used by different writers in each of these two ways. Although the definition of Roessler has historical precedence, the definition of form-factor used in several papers presented to us at this meeting seems to be now nearly universal, and it is probably now too late to revert to the original definition or to make any other change.

Chas. F. Scott: This instrument is essentially a practical instrument. The scientific principles which have been explained show that under a fairly wide variation of the very many variables which enter into the problem, it is substantially correct. To get a true idea of the value of the instrument, we must consider what must be done if this instrument were not available. Mr. Chubb has summarized the conditions which ordinarily apply, not only on the circuit of the operating company, but on the circuit of the manufacturing company in the testing laboratory. In order to get an accurate knowledge of the conditions of wave-form, it is necessary to make very elaborate, extended, and cumbersome measurements. It has been the custom at some factories to specify that a particular generator shall be used for supplying the current for transformer measurements and that the measurements are to be made on the machine when it is not loaded, it being known that the particular machine gives approximately a sine-wave. It recently happened that in a certain case transformers that were to be subjected to a certain test were measured with this new instrument, but it was found out afterwards that the generator, instead of being empty, as specified, was really carrying a load, and probably had a distorted wave form. In the days of the old method of measurement, with an ordinary voltmeter, there would be an error of probably twelve to fifteen per cent. The transformers, which had already been sent to the shipping room, were taken back and remeasured, and it was found that the measurements, under the corrected conditions, the specified conditions of the test, showed practically the same results as those formerly taken. Those who are the most familiar with the difficulties involved in the measurement of transformers, either in a large factory or at a remote station, will probably be the first to appreciate a method which is as good as this, although it may not be correct to the highest degree of refinement.

Charles P. Steinmetz: This instrument is extremely useful. We must realize, however, that in the usual case of transformer testing, where only a small amount of power is required, and therefore the efficiency of supplying the power is immaterial, we can get an almost absolutely perfect sine-wave from a circuit of any kind of wave shape, in the following manner. (Fig. 1). Suppose we have at *D* a supply of alternating voltage of known pressure and frequency, but of any kind of wave shape, no matter how distorted, and insert two inductances of equal reactance, *x*, into the circuit, and shunt a condenser, *C*, across the circuit, adjusting the condenser for the same reactance, *x*, as the inductances, so that if there is a short-circuit at *B*, there will be a minimum current from *D*. Then, connecting a resistance *r* across the circuit, and tapping off this resistance, a part of it or all, at *S*, any apparatus connected across *S*, if the current taken by it is small compared to the current in the resistance *r*, receives a perfect sine-wave. There is a case of resonance in this combination which eliminates everything but the fundamental sine-wave. This arrangement may be useful, at least for calibrating such a core-loss voltmeter; otherwise, after a year or so it may be doubtful whether the meter is correct or not.

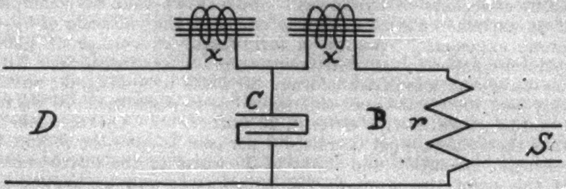


FIG. 1.

L. W. Chubb: Answering Dr. Bedell as to the reliability of calibration; we have used the instruments since March, 1908, and have had remarkably good results. Constancy of calibration was obtained by making the steel core of the instrument of laminated steel rings of non-aging material, without air-gaps and by thoroughly impregnating this core in a hard gum. Repeated calibration has shown the instruments to be reliable.

There is great need of such a method and instrument, as very large transformers cannot be even approximately tested by the usual method on the small generators that must be used for testing purposes. The new designs of transformer with silicon-steel cores, and their peaked exciting currents, will invariably distort the voltage wave of the testing generator, and unless the core-loss-voltmeter method, or the more complicated correction method, is used, the core-loss test is practically worthless.

Dr. Steinmetz suggests that the definition of form-factor be changed so as to give unity for the form-factor of a sine-wave. This would be a great convenience. The present method of having 1.11 as the sine form-factor introduces fractional coefficients in the usual formulas.

Dr. Lloyd speaks of the present government specifications for equipping and method of testing transformers, prohibiting the small producers from taking contracts. Such has been the case, but satisfactory specifications can certainly be written requiring the use of the core-loss voltmeter, which will allow the small producer to compete, and which will greatly simplify the tests of the larger companies. Table III and the oscillograms in this paper show results of tests made by the Navy Department with a view of adopting the method.

In regard to different metals which may be used in the transformer core. It makes practically no difference whether the transformer under test is built with sheet-iron, open-hearth, or silicon-steel. The same instrument can be used and the result of core loss will in all cases vary from the true sine-wave value much less than if the root-mean-square voltmeter is used. The curves of Fig. 5, show the errors introduced by different ratios of eddy and hysteresis losses. A general statement, with no figures, was made in regard to the effect of steels having different exponents of hysteresis. Suppose we take an example of an extreme case to show the effect of the variation of hysteretic exponent: Assume a form-factor of voltage of 1.20; hysteretic exponent of instrument core 1.6; of transformer 2.0; sine-wave core loss of transformer 80 watts hysteresis, 20 watts eddy loss, 100 watts total; sine-wave loss in instrument 16 watts hysteresis, 4 watts eddy current, 20 watts total. On the peaked wave the voltage must be raised 6 per cent to give the required voltmeter indication and input of 20 watts to the instrument. At this point the input to the transformer will be hysteresis 76.910 watts, eddy current 22.472 watts, total 99.382 watts. Indeed, it will be seen that the component hysteresis and eddy-current losses are very much in error; but one is practically as much low as the other is high, so that the sum is only 0.6 per cent in error. In this case we have considered the hysteretic exponents in instrument and transformer differing as much as will be found in service, and the error of less than 1 per cent is commercially allowable.

In regard to the portability of the instrument, it is certainly heavy as now made, but a much lighter instrument is being designed which will be quite portable.

Mr. Robinson expressed the opinion that it can be used only in certain cases. The experience we have had with the instrument shows clearly that such is not the case. Any transformer of a certain frequency which is of commercial design may be tested with any core-loss voltmeter, adjusted for that frequency, and in all cases, it may be said that the core-loss tests will be more accurate than with the usual voltmeter.

L. T. Robinson: I agree substantially with everything that has been said, that is, for ordinary conditions, but I do think the instrument should be used with considerable caution, because there are variations in form-factor on systems that might sometimes make it misleading to use an instrument like the one described.

L. W. Chubb: You mean that the purchaser of a transformer does not want to know the core loss on a form-factor of 1.11, but that he is interested in what the loss will be on his line.

The transformer which has the lowest loss on a sine wave will have the lowest loss on the customer's wave. Specifications and tests should all be based on the same wave, and then guarantees and test results will be directly comparable. The manufacturers do not know the form-factor of the customer's line. If they did it would not be practicable to work out special performance guarantees for the customer's circuit. It is far better to have a standard wave shape on which to base the performance, and require that the tests be made in terms of this standard wave, or sine wave. Such tests can be made with the iron-loss voltmeter on any commercial circuit.

The next question referred to the proportion of eddy current and hysteresis loss varying in the instrument. The percentage of hysteresis does vary at different scale readings, but within a readable range the ratio is sufficiently constant to give accurate results.

It was also suggested to use an instrument to find the form-factor and make corrections in the observed core-loss result. It should be remembered that if this is done it is necessary to make several elaborate tests and calculations, while with the iron-loss-voltmeter it is only necessary to adjust the voltage until the meter reads the normal value, and then read the core loss directly on a separate wattmeter.

Dr. Bedell suggests having the square type wave or the unity form-factor wave as standard, and then comparing other waves to it; in fact, treating the matter as in the case of power-factor. The unity power-factor is the most desirable and convenient reference value for the cosine of the angle of lag or lead, while the unity form-factor is a limiting as well as a maximum value, and a condition which is never acquired in the usual alternating-current circuits.

Dr. Steinmetz speaks of using a harmonic filter, as shown in his diagram, for obtaining a sine wave for testing transformers or calibrating the iron-loss voltmeter. The scheme will give a sine wave at S at no load, or when the current drawn at this point is very small in proportion to the current through the resistance. However, a transformer exciting current is a distorted low-power-factor current with a decided peak, when the values of voltage are low or going through zero. On account of this distorted and low-power-factor current there will be out-of-phase resistance drops in the resistances shown, which will peak the voltages at S.

The scheme outlined by Dr. Steinmetz could be used in calibrating meters taking very small current, but I believe the iron-loss voltmeter takes too much current to be successfully calibrated by this method.

In reply to the question concerning the form-factor correction scheme, I will say that oscillograms were not taken. However, voltage drops and currents were observed at the cell and at other points of the circuit. We found experimentally that the relative readings of the root-mean-square and iron-loss voltmeters, connected to the terminals of the transformer, could be easily and quickly adjusted by means of the inductance L and resistance R, thus making the form-factor correspond to a sine wave, a peaked or a flat wave.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

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THE TESTING OF TRANSFORMER STEEL

BY M. G. LLOYD AND J. V. S. FISHER

Summary. The object of this paper is to discuss the conditions which should be realized in the measurement of energy losses in sheet-iron and steel subjected to alternating magnetization, with a description of a modification of the Epstein method and apparatus. This method is believed better to satisfy the desired conditions and to give an accuracy of one per cent with the use of less than two kilograms (4.4 lb.) of material.

Results are given showing a wide range in the quality of material in general use, quality having slight connection with price. Several foreign specimens of ordinary steel and silicon-steel are included for comparison with the American product. Silicon-steels contain from 3 to 4 per cent silicon, the quality not depending upon the exact percentage of silicon.

By making measurements at two frequencies, the eddy-current and hysteresis losses have been separated and a study made of the variation of each with flux density. The values of the hysteretic constant and the total loss in watts per pound at 60 cycles and 10,000 gausses are tabulated.

The effects of artificial aging are shown to depend upon the flux density selected for test, the hysteresis increasing more for 5000 than for 10000 gausses. Tests should therefore be made at the density to be used. The aging is usually negligible in silicon-steels.

Many methods have been employed for the testing of sheet-iron and steel for energy losses when subjected to alternating magnetization, but all that have so far been employed have been lacking in some desirable qualifications. The plotting of a hysteresis loop from readings of magnetizing force and the resulting magnetic induction, and the measurement of the area of this loop, is a slow and tedious process and gives no indication of the eddy-current losses. Methods depending upon the relative motion of the specimen and a magnet necessitate an air-gap in the magnetic circuit, with a resulting induction in the specimen which is far from uniform. Moreover, if a permanent magnet be used, as in the Ewing and the Blondel apparatus, one is restricted in the values of the flux density which may be used, and the apparatus is suitable only for comparative measurements at one flux density.

Consequently, methods of testing with alternating currents have come to be regarded as the only satisfactory way of making these measurements, and present efforts are directed to securing the best conditions for this form of test. In the wattmeter method, the electrical energy which is supplied to maintain the alternating magnetization is measured with a wattmeter, while the maximum magnetic induction produced in the specimen is determined by a voltage measurement at the terminals of the magnetizing winding or at the terminals of a secondary winding placed around the same core of test material.

The specimen may be employed in three forms: (1) It may be in the form of straight strips placed in contact with a yoke, thus forming a closed circuit of ferro-magnetic material. (2) The straight strips may be used without any yoke. (3) The specimen may be arranged to form a closed magnetic circuit in itself.

The second form gives a distribution of flux which is far from uniform, and is therefore objectionable. The first form gives a more uniform flux, but it is necessary to distinguish between the energy supplied to the specimen and that supplied to the yoke. This can be done satisfactorily only by knowing the constants of the yoke, and only then by having the distribution of flux uniform, a condition difficult to secure. Consequently, for accurate measurements the third form is the most reliable, although for factory use the first or second may prove more convenient where accuracy can be sacrificed for other considerations.

Assuming a closed magnetic circuit of the material to be tested by the wattmeter method, the following conditions should be realized as far as possible:

1. The flux should be uniformly distributed over the cross-section of the specimen, and should be the same at every section; this requires that there should be no leakage of flux through the air.

2. A definite form of wave of magnetic flux should be used, or in other words, a definite form of wave of secondary electromotive force, since the form-factor of this wave enters into the computation of maximum flux density from the observed effective voltage.

3. The material used should be cut in a form such that only a small part of it is contiguous to a cut edge, since it is well known that all methods of cutting have a hardening effect upon the material bordering upon the cut. This means that the strip, whether straight or in ring form, should not be too narrow. This condition may be dispensed with if all specimens are annealed under definite conditions after cutting to size and prior to testing.

4. The amount of material required should not be greater than is necessary to get a fair average value.

5. The corrections to be made in the readings of the instruments to obtain final values should be as few and as small as possible.

Two general forms of magnetic circuit are available. The material may be stamped into rings or the circuit may be built up from straight strips. Leakage is most effectually avoided by using rings. With this form of specimen, however, it is impossible to satisfy simultaneously conditions 1 and 3, unless rings of very great diameter are employed, and in the latter case there is a very great waste of material. The non-uniformity of flux existing in rings of small diameter, even when uniformly wound, and the errors resulting therefrom, have been discussed elsewhere.[1] The use of rings is thus restricted to cases where the material is annealed after stamping, and the radial width of the ring should be very small in comparison with its diameter. When rings are employed, the labor of winding each specimen separately with a magnetizing coil may be obviated by the use of the apparatus of Esterline[2] or Möllinger.[3]

To meet condition 2 it is sufficient to know or measure the form-factor of the secondary voltage.[4] By making runs at two frequencies it is then possible to separate the eddy-current and hysteresis losses, and, if desired, to compute the eddy-current loss for a standard wave-form.[5]

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[1] M. G. Lloyd, Bulletin of Bureau of Standards, 5, p. 435; 1909. *Electrical World* 52, p. 1395; 1908.

[2] J. W. Esterline, Proc. Am. Soc. Testing Materials 3, p. 288; 1903.

[3] J. A. Möllinger, Elektrot. Zs. 22, p. 379; 1901.

It is far preferable, however, to work throughout with a sine wave, when a generator is available which will fulfill this condition. There are three things which may prevent the realization of this condition. In the first place the machine may not generate a sinusoidal electromotive force. In fact, it may be stated as a general proposition that no generator gives a perfect sine wave. The only question is as to the magnitude of the harmonics present, and whether these are negligible. It cannot be assumed that these are negligible simply because the machine was designed to give a sine wave, or because a rough oscillogram does not indicate definite distortion. The only way to be certain is to take an accurate curve from the machine and analyze it by measurement of the ordinates.

As an example of the necessity of this, we cite an instance occurring at the Bureau of Standards. Here the tests are usually made with a generator whose electromotive force wave contains a third harmonic whose amplitude is 0.6 per cent of the amplitude of the fundamental, and none of the higher harmonics are present to such an extent as 2 per cent. The form-factor is almost exactly that for a sine wave. One day a specimen, which had already been tested with this generator, was tested with a second generator supposed to give a sine wave whose oscillogram appeared smooth and inoffensive. The losses appeared more than 4 per cent lower than by the previous test. This led to a closer examination of the wave given by the generator, the wave being traced by the Rosa apparatus,[6] analyzed and found to contain nearly 7 per cent of the third harmonic, sufficient to account for the observed difference in losses.[7]

A second cause of distorted wave-form is to be found in armature reaction, which may alter the electromotive force of a loaded generator when the curve on no load is sinusoidal. For this reason, it is best in testing to use a machine so large that it is only slightly loaded by the test current.

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4. An apparatus for measuring form-factor is described by Lloyd and Fisher, Bull. Bur. Stds. 4, p. 469; 1908.

5. See M. G. Lloyd, Bulletin Bureau of Standards 5, p. 381; 1909

6. See E. B. Rosa, Phys. Rev. 6, p. 17; 1898. TRANS. A. I. E. E. 1898.

7. See M. G. Lloyd, Bulletin Bureau of Standards. 4, p. 484; 1908.

A third cause of distorted wave is to be found in the drop of potential due to the impedance of the circuit. The generator electromotive force is made up of two parts, one of which is balanced by the electromotive force induced by the changing flux, while the other produces current. If the flux be sinusoidal, the electromotive force induced by it is also sinusoidal. But owing to the fact that the permeability of the material varies with the magnetic induction, the magnetizing current cannot be sinusoidal. The component of the electromotive force producing current has the same form of wave as the current, and it also cannot be sinusoidal. The total electromotive force of the generator then, to produce sinusoidal flux, is made up of one component which is sinusoidal and one which is not, and therefore is not sinusoidal. Its shape must vary with varying conditions, and hence it would be useless to attempt to secure such a form of generator electromotive force. To approximate sinusoidal flux it is necessary to have a sinusoidal electromotive force at the generator and to make the component which sends current (equal to the product of current and resistance) negligible in comparison with the component which balances the electromotive force induced in the apparatus. It is desirable then to keep both resistance and current low in the magnetizing circuit. If this ohmic drop of potential can be made negligible, then the wave-form of flux will differ from a sine curve only by a negligible amount.

The resistance in the magnetizing circuit consists of the armature, leads, magnetizing coil, measuring instruments and perhaps of windings of transformers used to step up or down to the proper voltage. It should not include a regulating rheostat, but the current should be controlled through the generator field. Each of these items should be made as low as possible, and thus appears another reason for choosing a generator of capacity large in comparison to the load to be placed upon it. The magnetizing current may be kept low by having a magnetic circuit of low reluctance. Air-gaps should be avoided, and any joints in the magnetic circuit be made as good as possible.

With the same magnetizing current, the induced electromotive force is proportional to the cross-section of test material; consequently the greater the quantity of material used, the less the distortion of the wave. With a definite cross-section and windings, the induced electromotive force is proportional to the maximum flux density, but the magnetizing current is not proportional to the flux density, owing to varying permeability. The greater the permeability, the larger the ratio of flux to magnetizing current. The distortion will consequently be less if the iron be magnetized in the region of maximum permeability, and the distortion is sure to become appreciable if the flux density be carried too high, and may become appreciable at very low flux densities, even when it is negligible through the range of working flux densities used industrially.

In the method of Epstein,[8] which has been adopted as standard in Germany,[9] these conditions are fairly well met. Ten kilograms of sheet are cut into strips 50 by 3 cm. and assembled into four bundles, over which solenoids are slipped. The four bundles are arranged in the form of a square, having butt joints at the corners, where the magnetic material is separated by a sheet of thick paper. This interruption to the magnetic circuit tends to make the flux more uniform across the section of test material, but it also makes the leakage greater, and the flux less equal at different sections. Thus the flux at the center of one bundle may exceed the flux near one end by as much as 8 per cent. This air-gap also increases the reluctance of the magnetic circuit, consequently increasing the magnetizing current, and a large quantity of test material must be used. Condition 4 is here sacrificed for the better attainment of conditions 1, 2, and 3, and yet conditions 1 and 3 are not very well satisfied.

A modification of this method has been developed at the Bureau of Standards differing from the foregoing principally in the arrangement of the test material. A smaller quantity of material in wider strips may be used, while at the same time a greater uniformity of flux is secured. The amount of material used is from 1.5 to 2 kg. (less than 4 lbs.), and an accuracy of one per cent is attained.

DESCRIPTION OF THE APPARATUS

The specimen to be tested is cut into strips 25.4 by 5 cm. (10 by 2 inches). These are assembled into four bundles, in each of which adjacent strips are separated by strips of press board of equal width and thickness, but 2 cm. shorter. Each bundle is wrapped with friction tape and is inserted in a solenoid.

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[8] I. Epstein, Elektrotechnische Zeitschrift 21, p. 303; 1900.

[9] Elektrot. Zs. 24, pp. 657, 684; 1903.

The four bundles are then arranged in a square so that the plan view shows the edges of the strips, as in Fig. 1. The solenoids are wound upon fiber frames 22.7 cm. long, and have inside dimensions 5 cm. by 1 cm. At the corners of the square, short pieces of test material are bent at right angles and interleaved between the strips of adjacent bundles, as shown in the figure. There are as many of these corner pieces as there are test pieces, and they are graduated in length so as to give a uniform lap of about 2 mm. A special clamp, shown in Fig. 2, is tightened over these laps, so as to give a good magnetic joint.

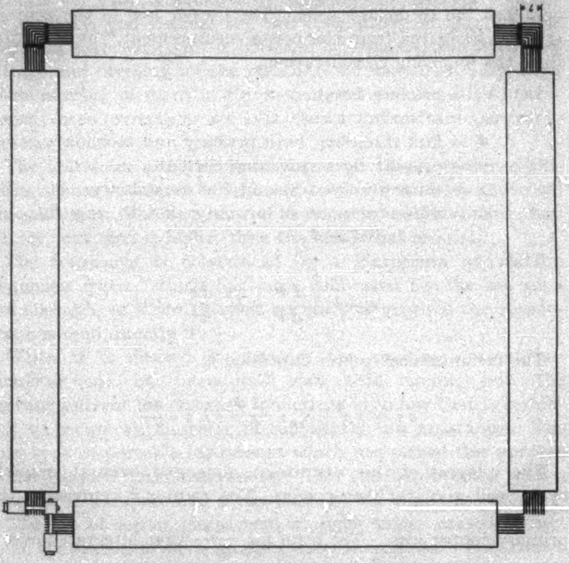

Fig. 1.—Plan of apparatus, showing corner pieces in place at two corners and clamp in place at one corner.

Each solenoid has in its first layer two windings of double-silk-covered No. 20 wire, each consisting of 45 turns. Over these are wound 250 turns of No. 14 copper wire, also double-silk-covered, to form a magnetizing coil. The four solenoids are connected in series, making a total of 1000 magnetizing turns and two secondaries of 180 turns each. One of these secondaries is connected to a voltmeter for determining the magnetic flux. This instrument is a deflecting mirror dynamometer, giving a sufficient deflection with 0.004 ampere. The other secondary is connected to the moving-coil circuit of a watt-dynamometer of the same type as the voltmeter. The magnetizing current traverses the field coils of this wattmeter, whose deflections are a measure of the power supplied to the core and the secondary coils. The copper loss in the primary is thus eliminated from the power measurement,[10] as is evident from the following considerations.

Let N_1 = primary turns.
N_2 = secondary turns.
Φ = flux threading both primary and secondary.
i = primary or magnetizing current.
e = electromotive force applied to primary.
L = self-inductance of primary due to any flux not included in Φ.

Then

$$e - N_1 \frac{d\,\Phi}{d\,t} - L\,\frac{d\,i}{d\,t} = ri$$

The instantaneous power expended is

$$e\,i = r\,i^2 + N_1\,i\,\frac{d\,\Phi}{d\,t} + L\,i\,\frac{di}{d\,t}$$

The integral of this expression, extended over a complete cycle, will give the net power. The term $r\,i^2$ represents the primary copper loss. The term $L\,i\,\frac{d\,i}{d\,t}$ when integrated over a complete cycle, is equal to zero. The term $N_1\,i\,\frac{d\,\Phi}{d\,t}$ will not integrate to zero when there is either hysteresis in the core or secondary currents (including eddy currents) are flowing, since in either case Φ is not in phase with i. This term represents the power expended in the core and in the secondary circuits. $N_2\,i\,\frac{d\,\Phi}{d\,t}$ is proportional to this, and its integral value represents the reading of the wattmeter when connected as in this apparatus. Hence the wattmeter reading, when multiplied by $\frac{N_1}{N_2}$, gives the power expended in the core and in the secondary circuits. Error will arise only when there is flux threading the core and linked with the primary, which is not linked with the secondary. This is avoided by winding the secondary under the primary, and making the two coextensive in length. The energy in each secondary is obtained by squaring the secondary voltage and dividing by the resistance of its circuit. By using a low number of turns in the secondaries and sensitive instruments, these corrections are kept very small and are accurately known.

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[10] Due to C. P. Steinmetz, TRANS. A.I.E.E., Vol. IX, p. 624; 1892.

The voltmeter and the wattmeter each have variable multipliers, whose resistance is adjusted to give a suitable deflection in each case. The accuracy of reading is usually better than 0.1 per cent, and is higher than the conditions require.

The frequency is determined by a Hartmann and Braun frequency meter, which has been calibrated by the use of a chronograph, or where greatest accuracy is required the chronograph is read directly.[11]

When it is desired to measure the exciting current, an ammeter can be introduced into this circuit, but the exciting current for ordinary inductions is so low that it is difficult to secure an ammeter of sufficiently low resistance. The only type of portable instrument which has served this purpose is the Duddell thermo-ammeter. This can be obtained with a range of 0.5 ampere and a resistance of 0.2 ohm.

The use of corner pieces bent at right angles caused at first some apprehension as to its effect upon the results. It is known that bending, like any other mechanical treatment, will change the magnetic properties of the steel. If this affected enough of the steel seriously to alter the average value, it would condemn the method. Experiments which were directed to the determination of this effect showed that it was of no importance. The corner pieces are bent sharply in a machine which distorts the material to only a very short distance from the angle. The distorted material has its constants considerably changed without doubt, but as the corner pieces constitute only about 5 per cent of the entire circuit, and as only a part, say 30 per cent, of this material is altered by a fraction, say 20 per cent, of its initial value, an error of much less than 1 per cent is made by regarding this material as unaffected by the bending, and 1 per cent is the limit of accuracy claimed for the method.

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[11] This use of the chronograph, with specimen record, is described by M. G. Lloyd, Bulletin Bureau of Standards, 5, p. 388; 1909.

To examine experimentally the effect of bending, a measurement was made in the usual way; the strips were then removed and each was bent at right angles and then bent straight at a point close to the first bend, so that the length was only slightly altered. A new measurement showed that the losses had increased by 1 per cent. A single bend would of course affect them by much less than this. Another experiment consisted in making measurements upon annealed specimens, and others not annealed, each with corner pieces of its own material. The corner pieces not annealed were then used with annealed test pieces, and after making the proper corrections and allowances for loss in the corner pieces, as described later, the values for the test pieces were found in agreement with those previously obtained with annealed corner pieces. As the annealed material is very much more sensitive to mechanical treatment than that not annealed, the effect must have caused different results in the two cases if it were operative to more than a negligible degree. A third method of checking this point was tried, and led to the same conclusions, but the foregoing are considered sufficient evidence.

On account of the lapping of the corner pieces over the ends of the test pieces, the flux density is low in this part of the material, necessitating a correction in the results. The amount of lap is determined by the relative weights of corner and test pieces, as compared with the relative lengths of the two parts of the circuit. When the corner pieces are of the same material as the test pieces, it is assumed that the flux density is halved in the portion of material which laps, and the energy loss is consequently only one-third normal.

B = nominal, or average, maximum flux density.
B_1 = maximum flux density at ends of test pieces.
M = mass of test pieces.
m = mass of corner pieces.
l = dimension shown in Fig. 1.
W = measured loss.

$\frac{m}{M}$ = proportional increase in mass of magnetic circuit, due to corner pieces.

$\frac{l}{25.4}$ = proportional increase in length of magnetic circuit, due to corner pieces.

$\frac{m}{M} - \frac{l}{25.4} = c$ = mass of corner pieces which lap, expressed in terms of mass of test pieces.

$2c$ = total material (lapped and lapping steel) in which flux density is $\frac{B_1}{2}$

$$2cW\left[1-\left(\frac{B_1}{2B}\right)^x\right] = 2cWk = \text{correction to } W \text{ for lap,}$$

where x expresses the law of variation of loss with B.

k varies slightly with the conditions. If $B_1 = B$ (no leakage)

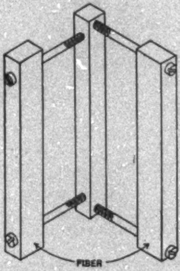

FIG. 2.

and $x = 1.6$, $k = 0.67$. For $x = 2.0$ this becomes 0.70. For 4 per cent leakage, $x = 1.6$, $k = 0.68$. With sufficient accuracy for the purpose k may be taken as 0.70 throughout, so that the correction becomes $1.4\ cW$ and the loss per unit mass is $\frac{W}{M+m}(1+1.4c)$ or $\frac{W}{(M+m)(1-1.4c)}$ with sufficient accuracy. The latter form is the most useful in practice, since a number of observations at different flux densities are usually made upon a single specimen, and the correction may be made once for all to the mass. The quantity $(M+m)(1-1.4c)$ may be called the "effective mass."

At first, a set of corner pieces was made for each set of test pieces of the same material, but this has been found unnecessary.

Corner pieces of approximately the same quality and thickness may be used with satisfactory and reliable results, provided the constants of the material are known. The Bureau of Standards has now accumulated a sufficient variety of corner pieces so that it is seldom necessary to make a new set, unless unusual precautions are to be taken. When using corner pieces of different material from the test pieces, it is necessary to compute the loss in the entire corner pieces, and then determine an "effective mass" resulting from the lap reducing the flux in the test pieces, Since the thickness of corner pieces may be different from that of the test pieces, it is necessary to consider this fact, and the flux at the lap may be considered to divide evenly between the two, or in proportion to their thickness. As the results do not differ materially, we assume that in each lapped part the flux density is half the value in the rest of the material.

Let

t = thickness of test pieces.
t_1 = thickness of corner pieces.
w = loss per unit mass in corner pieces.

and other quantities as before. We neglect the leakage, which is small. c must now be computed by using for M the mass M_1 of test pieces of the same material as the corner pieces. The loss in the corner pieces, if there were no lap, would be $w\, m \left(\frac{t}{t_1}\right)^x$.

Considering the effect of lap the loss is $w\,(m - 0.7\, c\, M_1) \left(\frac{t}{t_1}\right)^x = W_c$. The correction to be applied to the loss in test pieces due to lap is $0.7\, c\, (W - W_c)$ and the loss per unit mass is $\frac{W - W_c}{M\,(1 - 0.7\, c)}$.

If the corner pieces are of the same thickness as the test pieces, the loss in them becomes $w\,(m - 0.7\, c\, M_1)$, and this expression will usually give the correction closely enough. Here again the quantity $(m - 0.7\, c\, M_1)$ can be determined once for an entire set of measurements.

If the flux at the lap be assumed to divide between the two in proportion to thickness, we have for the loss in the corner pieces

$$w\left[\,(m - c\,M_1)\left(\frac{t}{t_1}\right)^x + c\,M_1\left(\frac{t}{t+t_1}\right)^x\right]$$

and the correction for lap in the test pieces is

$$c\,(W - W_c)\left[1 - \left(\frac{t}{t+t_1}\right)^x\right]$$

The leakage with this arrangement of test material, that is, the difference between flux at the ends of test piece and at the middle, is usually not greater than one per cent. Since the greatest length of a line of induction is 8 per cent larger than the least, there is a probability of the same difference in flux density between the outer and inner sheets. As the average flux density is measured, this cannot make an error greater than a small fraction of one per cent.[12] Inequality in the four arms has an equally slight effect. Upon removing one sheet in 12 from opposite sides, the loss per unit mass was not appreciably altered.

OBSERVATIONS AND RESULTS

The procedure in making a test is as follows: The material is cut into strips of the given dimensions by the use of a sharp machine shear with nearly parallel jaws. The number of strips is determined by the thickness, and for gauge No. 29 amounts to 48. The strips are then weighed, bundled and mounted in the solenoids. The effective voltage corresponding to any given flux density and frequency is computed from the following relation.

$$E = 4\,f\,N\,n\,\Phi\,10^{-8} = \frac{4.44\times180\times10^{-8}\,B\,n\,M}{101.6\,\rho}$$

where n = frequency, Φ = total flux, f = form-factor of the secondary electromotive force, and ρ = density. In the work here reported ρ has been taken as 7.77 grams per cubic centimeter, but it is proposed hereafter to determine the density for each specimen.

The dynamometer voltmeter is calibrated for one voltage as determined above, and when taking observations for watt loss, the generator voltage is adjusted until the same deflection is obtained. For other frequencies and flux densities, the resistance in the voltmeter circuit is altered until it is proportional to the product $B\,n$, so that the same deflection is always used. For the lower values of this resistance, the slight correction due to the inductance of the instrument is also made. In computing the power supplied to the voltmeter circuit, it may then be remembered that this energy is also proportional to $B\,n$, since the same current is used throughout. A similar series of resistances is usually used in the potential circuit of the wattmeter, so that the power consumed here is also readily computed. The deflection, however, will increase as the product $B\,n$ increases, but will usually remain within working limits of permissible deflections. These limits are so chosen that within them the deflections are proportional to the watts. The multipliers for the potential circuit are so chosen that for one of them the actual watts corresponding to a given deflection, when multiplied by $\frac{N_1}{N_2} = \frac{1000}{180}$, are numerically equal to the deflection. The wattmeter is then direct-reading for this range for the values of the watts required, and for other ranges a simple factor determined by the value of $B\,n$ gives the desired result.

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[12] See M. G. Lloyd, Bulletin Bureau of Standards, 5, p. 435; 1909.

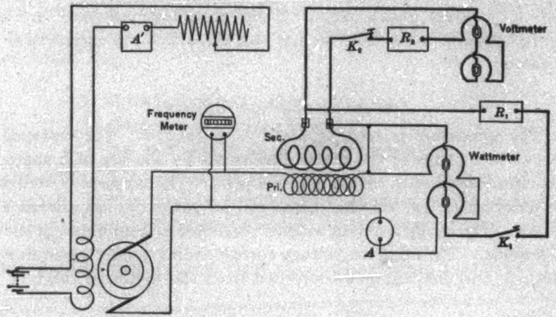

Fig. 3.—Diagram of connections.

The generator used gives an electromotive force wave which is sufficiently close to the sinusoidal, and the form-factor of the secondary electromotive force has been determined and found sufficiently near to that assumed through the working ranges of flux density at the frequencies used, which usually are 60 and 30 cycles, the latter being chosen because it makes the separation of hysteresis and eddy-current losses easy to compute. The generator is driven by an electric motor whose field circuit contains a rheostat in the laboratory, permitting adjustment of speed for a definite frequency. The motor is supplied with power from a storage battery so that a steady speed may be maintained. The field circuit of the generator is connected through another rheostat in the laboratory, which permits adjustment of the generator voltage to give the flux density desired. No rheostat is used in the magnetizing circuit. When necessary, a transformer of ample capacity is used to step up or down to the voltage required for the test.

The electrical connections are shown in Fig. 3, where for simplicity a single secondary is represented, which may indeed be used in practice. When the generator voltage has been adjusted to give the proper reading on the voltmeter connected to the secondary circuit, the wattmeter is read. These settings are repeated twice. An adjustment is then made for a different flux density and readings are taken as before. When the exciting current is desired, an ammeter is included in the magnetizing circuit, and its indications noted. Whenever a change is made from a higher to a lower flux, the current is reduced gradually to the lower value in order to demagnetize the material. This descending set of observations is usually made at a frequency of 30 cycles. Whenever the magnetizing circuit has been broken, it is closed through a considerable resistance, which is continuously reduced to zero in order to prevent a large first surge and consequent high magnetization, which would require subsequent demagnetization.

TABLE I.

SPECIMEN K

TEST PIECES = 1327 GRAMS. CORNER PIECES = 80.2 GRAMS. c = 0.029.

EFFECTIVE MASS = 1350 GRAMS

Cycles	Flux density	Wattmeter deflection	Watts	Instrument losses	Iron losses	Joules per cycle	Ergs per gram per cycle	Hysteresis	Eddy currents
60	10000	21.38	4.276	0.079	4.197	0.0699	518	394	124
30	10000	18.87	1.887	0.0395	1.848	0.0616	456	394	62
60	5000	13.54	1.354	0.0395	1.314	0.0219	162	130	32
30	5000	12.20	0.610	0.0197	0.590	0.0197	146	130	16

Table I gives a specimen set of observations where the corner pieces were of the same material, while in Table II they were of different material.

The total loss is separated into two components, due respectively to hysteresis and eddy currents, as follows, using the Steinmetz equation,

$$W = \eta \, n \, B^x + \zeta \, n^2 \, B^y$$

where the symbols have the same significance as before, η and ζ being constants of the material. By taking observations at two frequencies, n_1 and n_2 we have

$$\frac{W_1}{n_1} = \eta \, B^x + \zeta \, n_1 \, B^y = a + b \, n_1$$

TABLE II

SPECIMEN H_1

TEST PIECES = 1304 GRAMS. CORNER PIECES OF SPECIMEN K = 80.2 GRAMS. $c = 0.029$. EFFECTIVE MASS = 1278 GRAMS

Cycles	Flux density	Watt-meter deflection	Watts	Instrument losses	Iron losses	Joules per cycle	Corner pieces	Test pieces	Ergs per gram per cycle
60	10000	21.55	4.310	0.076	4.234	0.0706	0.0028	0.0678	531
30	10000	18.95	1.895	0.038	1.857	0.0619	0.0024	0.0595	465
60	5000	13.74	1.374	0.038	1.336	0.0223	0.0009	0.0214	168
30	5000	12.34	0.617	0.019	0.598	0.0199	0.0008	0.0191	150

$$\frac{W_2}{n_2} = \eta \, B^x + \zeta \, n_2 \, B^y = a + b \, n_2$$

where a is the hysteresis loss per cycle and $b \, n$ the eddy-current loss per cycle.

$$a = \frac{\frac{W_2}{n_2} n_1 - \frac{W_1}{n_1} n_2}{n_1 - n_2}$$

$$b = \frac{\frac{W_1}{n_1} - \frac{W_2}{n_2}}{n_1 - n_2}$$

If $n_1 = 2\,n_2$ this computation is greatly simplified; for then

$$b\,n_2 = \frac{W_1}{n_1} - \frac{W_2}{n_2}$$

$$b\,n_1 = 2\,b\,n_2$$

$$a = 2\,\frac{W_2}{n_2} - \frac{W_1}{n_1} = \frac{W_2}{n_2} - b\,n_2$$

While the Steinmetz equation, and consequently this separation, is not accurately in accordance with the facts, the errors are very small in thin sheets. The exponents x and y can be determined by observations at different flux densities, and these have been computed for a number of specimens, as shown in Tables III to VII. Where the eddy-current loss is small, as in silicon-steel, the values of y are subject to greater error.

TABLE III

VARIATION OF EXPONENTS WITH FLUX DENSITY

SPECIMEN P_1

Cycles	B	Loss per cycle	Hysteresis	Eddy currents	Exponents	
					Hysteresis	Eddy currents
60	12000	842.7	445.7	397.0		
30	12000	644.2	445.7	198.5		
60	10000	576.8	302.8	274.0	2.12	2.03
30	10000	439.8	302.8	137.0		
60	8000	381.4	204.8	176.6	1.75	1.97
30	8000	293.1	204.8	88.3		
60	6000	230.9	126.5	104.4	1.68	1.83
30	6000	178.7	126.5	52.2		
60	4000	114.9	67.9	47.0	1.53	1.97
30	4000	91.4	67.9	23.5		
60	2000	35.4	23.8	11.6	1.51	2.03
30	2000	29.6	23.8	5.8		

While these exponents do not exhibit any definite and constant value, it will be noticed that the hysteresis exponent does not differ much from 1.6 for flux densities between 5000 and 10000 gausses, while for densities exceeding 10,000 it is in the neighborhood of 2, with a definite tendency upward. The exponents for eddy-current loss vary rather widely from 2 in some instances, but with specimen *C* in Table VII, where the eddy-current loss is greater and the results consequently more accurate, the values come close to 2.

In order to test the proportionality between eddy-current loss and frequency, some runs were made with a second generator which gave 180 cycles at normal speed and 90 cycles at half speed. The wave-form of this generator is not so pure as that of the one used for the lower frequencies, but the loss could be altered by less than two per cent at most from this cause, and probably not over one per cent. The error from this cause would be less at 180 cycles than at 90 cycles. The measured loss, however, is a great deal lower at 180 cycles than is computed from the results at 30 and 60 cycles. This is illustrated by the experiments exhibited in Table VIII, where the hysteresis and eddy-current losses are separated by use of the readings at 30 and 60 cycles. The hysteresis is assumed constant, and the resulting eddy-current loss does not increase as rapidly as the frequency. The eddy-current loss falls off more rapidly, the thicker the specimen. The effect is greatly accentuated in specimen *A*, which consists of sheets 1.6 mm. thick, and was tested by using butt joints at the corners of the apparatus. The results of specimen *P* are plotted in the curve of Fig. 4. The

TABLE IV
VARIATION OF EXPONENTS WITH FLUX DENSITY
SPECIMEN *K*

Cycles	Flux density	Loss per cycle	Hysteresis	Eddy currents	Exponents	
					Hysteresis	Eddy currents
60	12500	820	638	182		
30	12500	729	638	91	2.16	1.7
60	10000	518	394	124		
30	10000	456	394	62	1.71	1.9
60	7500	313	241	72		
30	7500	277	241	36	1.53	1.9
60	5000	162.2	129.2	33		
30	5000	145.7	129.2	16.5	1.47	2.0
60	2500	54.6	46.6	8.0		
30	2500	50.6	46.6	4.0		

TABLE V
VARIATION OF EXPONENTS WITH FLUX DENSITY
SPECIMEN W_1

Cycles	Flux density	Loss per cycle	Hysteresis	Eddy currents	Exponents	
					Hysteresis	Eddy currents
60	12500	379	309	70.		
30	12500	344	309	35.	2.04	2.0
60	10000	241	196	45.		
30	10000	218.5	196	22.5	1.68	1.9
60	7500	146.8	120.8	26.0		
30	7500	133.8	120.8	13.0	1.60	2.0
60	5000	74.7	63.1	11.6		
30	5000	68.9	63.1	5.8	1.59	2.2
60	2500	23.6	21.0	2.6		
30	2500	22.3	21.0	1.3		

TABLE VI
VARIATION OF EXPONENTS WITH FLUX DENSITY
SPECIMEN *R*

Cycles	Flux density	Loss per cycle	Hysteresis	Eddy currents	Exponents	
					Hysteresis	Eddy currents
60	14000	606	524	82		
30	14000	565	524	41	1.88	1.6
60	12000	456	392	64		
30	12000	424	392	32	1.71	2.1
60	10000	331	287	44		
30	10000	309	287	22	1.68	1.7
60	8000	227	197	30		
30	8000	212	197	15	1.58	2.2
60	6000	141	125	16		
30	6000	133	125	8	1.65	1.65
60	4000	72.2	64	8.2		
30	4000	68.1	64	4.1	1.69	1.8
60	2000	22.1	19.7	2.4		
30	2000	20.9	19.7	1.2		

intercept of this curve upon the vertical axis represents the hysteresis loss. A dotted straight line has been drawn through the points for 30 and 60 cycles. We cannot be far wrong in assuming that the curve coincides with this at low frequencies, and consequently the method used for the separation of hysteresis and eddy-current losses is justified for thin sheets.

The falling off of the eddy-current loss at higher frequencies is explained by the consideration that the magnetizing force of the eddy currents reduces the flux in the center and crowds it towards the surfaces of the specimen; the short eddy-current paths enclose a smaller flux, while the longest still enclose the same; hence the average electromotive force of the eddy circuits does not increase as fast as the frequency.

TABLE VII
VARIATION OF EXPONENTS WITH FLUX DENSITY
SPECIMEN *C*

Cycles	Flux density	Joules per cycle	Hysteresis	Eddy currents	Exponents	
					Hysteresis	Eddy currents
60	13000	0.3554	0.2872	0.0682		
30	13000	0.3213	0.2872	0.0341	1.82	1.96
60	11000	0.2611	0.2119	0.0492		
30	11000	0.2365	0.2119	0.0246	1.59	2.00
60	9000	0.1868	0.1540	0.0328		
30	9000	0.1704	0.1540	0.0164	1.53	1.98
60	7000	0.1247	0.1047	0.0200		
30	7000	0.1147	0.1047	0.0100	1.48	1.93
60	5000	0.0741	0.0637	0.0104		
30	5000	0.0689	0.0637	0.0052	1.43	1.96
60	3000	0.0345	0.0307	0.0038		
30	3000	0.0326	0.0307	0.0019		

Some experiments were made with thick copper sheets in a solenoid. On account of the low flux densities secured, small quantities of energy had to be measured and the accuracy was not high, but the results indicated that the eddy-current loss did not increase as rapidly as n^2, but somewhat more rapidly than B^2. The latter result is, however, somewhat doubtful.

By taking readings upon an ammeter in the magnetizing circuit, it is possible to compute the wattless component of exciting current, and a curve of such values is plotted in Fig. 5 in relation to the flux density. Such a curve is just as valuable to the designer, or perhaps more valuable, than a magnetization curve obtained by the ballistic method. A similar curve for silicon-steel is plotted in the same figure. A ballistic curve which has been obtained by Dr. C. W. Burrows for a sample of silicon-steel from the same source, but from a different lot, is also shown but to a different scale. The low magnetizing current required by silicon-steel at low flux densities makes it particularly suitable for current transformers which must have close regulation, as when used with measuring instruments.

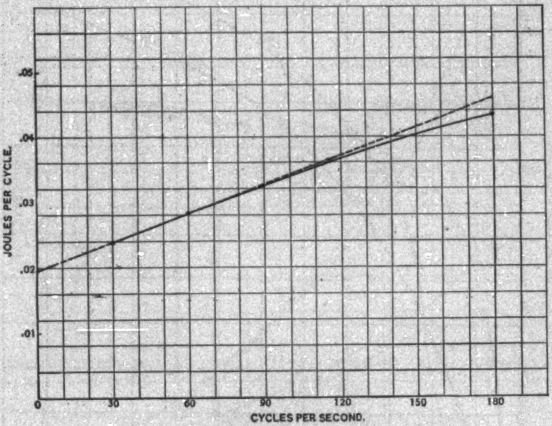

FIG. 4.—Transformer sheet No. 27 gauge at 5000 gausses.

That the hysteresis loss is larger when the steel is magnetized normal to the direction of rolling, than when magnetized parallel to the direction of rolling, is shown by Table IX and the curves of Fig. 6. The eddy-current loss in the two cases is practically the same, but the hysteresis is 5 to 10 per cent higher for magnetization normal to the direction of rolling. This specimen is of basic open-hearth steel, but the fact is typical of steel from all sources, though the magnitude of the effect is very variable. Table X shows a similar test upon steel from another source.

The authors have made tests of sheet-iron and steel from a great variety of sources, and have been surprised at the great range in quality of the material in general use by electrical manufacturers, the quality usually having no close relation to the price. Table XI shows some of the results obtained, all the materials having been secured from electrical manufacturers, or from iron mills and dealers supplying the electrical trade. Some foreign samples have been included in the table for comparison. The values of η have been computed from the relation $\frac{W}{n} = \eta B^{1.6}$; where $\frac{W}{n}$ is the hysteresis loss in ergs per cubic centimeter per cycle at 10,000 gausses.

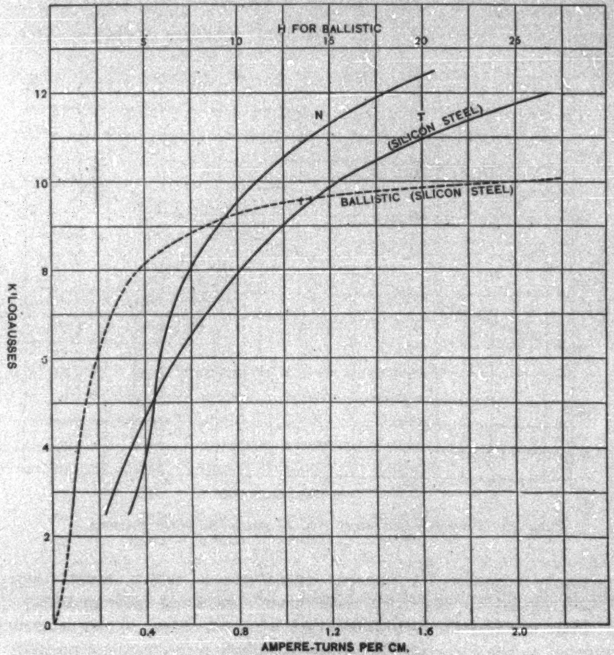

Fig. 5.—Magnetization curves.

The adjustments can be made and the readings taken so quickly after the circuit is closed, that the specimen becomes heated appreciably only when it is of poor quality or when extremely high frequencies or flux densities are used. The results consequently apply to room temperature. This varies from time to time through several degrees, but it has not been thought necessary to give the temperature in each case. The hysteresis varies only slowly with the temperature, and the eddy-current loss, which varies more rapidly, is the smaller part of the total, especially with silicon-steel.

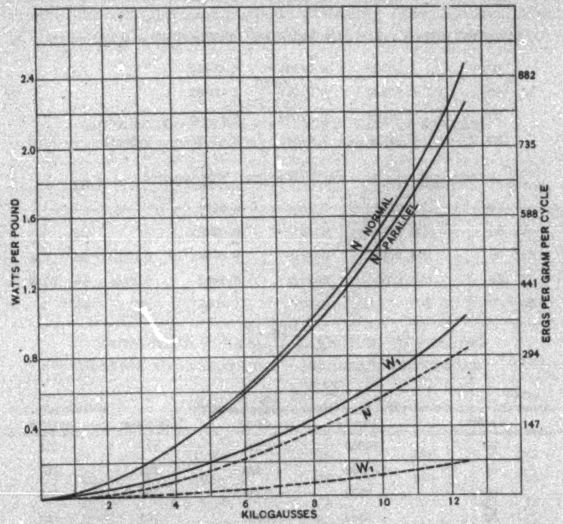

FIG. 6.—Relation between flux density and losses at 60 cycles when magnetized parallel and normal to direction of rolling. Solid lines represent total loss, dotted lines eddy-current loss, difference is due to hysteresis. N = ordinary steel; W_1 = silicon-steel.

Specimens P and P_1 should perhaps be classed as silicon-steels, although their silicon is not in the proportion which is typical of the alloy. Moreover, they are not put upon the market as an alloy steel, but are sold at about the price of

TABLE VIII

VARIATION OF EDDY-CURRENT LOSS WITH FREQUENCY

SPECIMEN *C*. $B = 5000$ GAUSSES. THICKNESS = 0.0422 cm.

Cycles	Joules per cycle	Hysteresis	Eddy currents observed	Eddy currents computed	Difference per cent
30	0.06844	0.06221	0.00623		
60	0.07467	0.06221	0.01246		
90	0.08074	0.06221	0.01853	0.01869	0.9
180	0.09626	0.06221	0.03405	0.03738	9.8
SPECIMEN *P*. $B = 5000$ GAUSSES. THICKNESS = 0.0437 cm.					
30	0.02385	0.01944	0.00441		
60	0.02826	0.01944	0.00882		
90	0.03249	0.01944	0.01305	0.01323	1.5
180	0.04329	0.01944	0.02385	0.02646	11.0
SPECIMEN A_1. $B = 3000$ GAUSSES. THICKNESS = 0.16 cm.					
30	0.0781	0.0510	0.0271		
60	0.1052	0.0510	0.0542		
90	0.1263	0.0510	0.0753	0.0813	7.4
180	0.1765	0.0510	0.1255	0.1626	22.8

TABLE IX

SPECIMEN *N*

MAGNETIZED PARALLEL TO DIRECTION OF ROLLING

Cycles	Flux density	Ergs per gram per cycle	Hysteresis	Eddy currents
60	10000	531	321	210
30	10000	426	321	105
60	7500	318	196	122
30	7500	257	196	61
60	5000	161	105	56
30	5000	133	105	28

MAGNETIZED NORMAL TO DIRECTION OF ROLLING

Cycles	Flux density	Ergs per gram per cycle	Hysteresis	Eddy currents
60	10000	562	352	210
30	10000	457	352	105
60	7500	332	208	124
30	7500	270	208	62
60	5000	167	110	57
30	5000	138.5	110	28.5

ordinary steel; hence they are classified as such. None of the samples analyzed showed more than the slightest trace of vanadium. Specimen *Q* contained 0.3 per cent of aluminum. For the chemical analyses we are indebted to Dr. H. C. P. Weber and Mr. J. R. Cain, of the Bureau of Standards.

Artificial aging has been practiced upon a number of the specimens, and consists in baking in an oven whose temperature is kept between 90 degrees and 100 degrees cent. The baking is interrupted only for the purpose of taking observations, which is done after the specimen has cooled to the room temperature.

TABLE X

SPECIMEN P_1

MAGNETIZED PARALLEL TO DIRECTION OF ROLLING

Cycles	Flux density	Ergs per gram per cycle	Hysteresis	Eddy currents
60	10000	576	302	274
30	10000	439	302	137
60	5000	168	96	72
30	5000	132	96	36

MAGNETIZED NORMAL TO DIRECTION OF ROLLING

Cycles	Flux density	Ergs per gram per cycle	Hysteresis	Eddy currents
60	10000	608	336	272
30	10000	472	336	136
60	5000	175	103	72
30	5000	139	103	36

The results are shown in Table XII, where the per cent change in total loss is given after various periods of aging. The time given is only approximate. The silicon-steels are almost entirely free from aging, but all the other specimens tested aged considerably, except L_1, and the test upon this was not continued for a very long period.

Caution must be exercised in applying the results of such tests, as one may be easily misled by them. Thus the hysteresis and eddy-current losses may be differently affected and, moreover, the hysteresis at different flux densities may be differently

TABLE XI

Designation	Thickness	Ergs per gram per cycle							
		10000 gausses				5000 gausses			
		60 cycles	30 cycles	Hysteresis	Eddy currents at 60~	60 cycles	30 cycles	Hysteresis	Eddy currents at 60~
Not annealed	cm								
A	0.0399	1785	1692	1599	186	608	585	562	46
B	0.0326	1290	1223	1156	134	420	402	384	36
C	0.0422	1274	1153	1032	242	426	391	356	70
D	0.0381	1193	1101	1009	184	401	377	353	48
Annealed									
E	0.0476	971	853	735	236	304	275	246	58
F	0.0280	766	716	666	100	247	233.5	220	27
G	0.0394	773	668	563	210	247	220	193	54
**H*	0.0307	558	485	412	146	177.5	158	138.5	39
*H_1	0.0277	531	465	399	132	168	150	132	36
J	0.0318	543	442	341	202	166.5	139	111.5	55
**K*	0.0282	518	456	394	124	162	146	130	32
*K_1	0.0280	541	479	417	124	170	152	134	36
†*L*	0.0346	565	473	381	184	175	150	125	50
†L_1	0.0366	615	516	417	198	192	165	138	54
B_1	0.0338	554	454	354	200	173	144.5	116	57
M	0.0335	550	461	372	178	173	150	127	46
N	0.0340	531	426	321	210	161	133	105	56
N_1	0.0312	523	435	347	176	162.5	137.5	112.5	50
P	0.0437	518	426	334	184	157	132	107	50
P_1	0.0470	576	439	302	274	168	132	96	72
Silicon-steels									
†*Q*	0.0361	357	330	303	54	113	105.5	98	15
†Q_1	0.0366	390	360	330	60	124	117	110	14
R	0.0315	330	309	288	42	104	98.5	93	11
S	0.0452	350	314	278	72	108	99	90	18
T	0.0338	310	280	250	60	96	87	78	18
U	0.0346	312	291	270	42	98	92	86	12
U_1	0.0325	322	300	278	44	101	94	87	14
**V*	0.0310	298.5	275	251.5	47	92	85.5	79	13
*V_1	0.0297	303	280	257	46	93	87	81	12
**W*	0.0305	240	218.5	197	43	74.7	68.5	62.3	12.4
*W_1	0.0311	241	218.5	196	45	74.7	68.9	63.1	11.6
X	0.0430	265	232.5	200	65	80.8	72.5	64.2	16.6

* German.
† English.

TABLE XI.—Continued.

Designation	x	y	η	Per cent silicon	Watts per pound at 60 cycles and 10000 gausses		
					Eddy-current loss for gauge No. 29 see note	Hysteresis	Total
Not annealed							
A	1.51	2.02	0.0049		0.41	4.35	**4.76**
B	1.59	1.89	0.00358		0.44	3.14	**3.58**
C	1.51	1.79	0.00319		0.47	2.81	**3.28**
D	1.52	1.94	0.00312		0.44	2.74	**3.18**
Annealed							
E	1.58	2.02	0.00227		0.36	2.00	**2.36**
F	1.60	1.88	0.00206		0.44	1.81	**2.25**
G	1.54	1.96	0.00174		0.47	1.53	**2.00**
*H	1.58	1.90	0.00127		0.54	1.12	**1.66**
*H_1	1.60	1.87	0.00123		0.60	1.08	**1.68**
J	1.62	1.88	0.00105	0.0	0.70	0.93	**1.63**
*K	1.61	1.90	0.00122		0.54	1.07	**1.61**
*K_1	1.62	1.82	0.00129	0.4	0.55	1.13	**1.68**
†L	1.61	1.88	0.00118		0.535	1.035	**1.57**
†L_1	1.60	1.87	0.00129		0.515	1.135	**1.65**
B_1	1.61	1.81	0.00110	0.0	0.61	0.96	**1.57**
M	1.55	1.95	0.00115		0.55	1.01	**1.56**
N	1.62	1.90	0.00099		0.63	0.87	**1.50**
N_1	1.63	1.81	0.00107		0.64	0.94	**1.58**
P	1.64	1.88	0.00103	1.3	0.34	0.91	**1.25**
P_1	1.66	1.92	0.00094	0.7	0.43	0.82	**1.25**
Silicon-steels							
†Q	1.63		0.00094	3.1	0.14	0.825	**0.965**
†Q_1	1.58		0.00102		0.16	0.90	**1.06**
R	1.64		0.00089	3.4	0.15	0.78	**0.93**
S	1.63		0.00086	3.5	0.12	0.755	**0.875**
T	1.68		0.00077	2.8	0.18	0.68	**0.86**
U	1.66		0.00084		0.12	0.735	**0.855**
U_1	1.68		0.00086	3.9	0.145	0.755	**0.90**
*V	1.68		0.00078		0.17	0.685	**0.855**
*V_1	1.67		0.00080	3.8	0.18	0.70	**0.88**
*W	1.67		0.00061	3.4	0.16	0.535	**0.695**
*W_1	1.64		0.00061		0.16	0.535	**0.695**
X	1.65		0.00062	3.2	0.12	0.545	**0.665**

NOTE.—In order to make a fair comparison the eddy-current loss has been computed for a thickness of 0.0357 cm. (gauge No. 29), assuming the loss proportional to the square of the thickness.

altered. In the present cases, measurements were also made at 5,000 gausses and at 30 cycles. Separation of the losses after aging indicates which component is active. It is found that the hysteresis is nearly always responsible for the increase, although the eddy-current loss may be either increased or diminished.

The decrease in eddy-current loss may sometimes mask the increase in hysteresis. Thus specimen Q_1 immediately exhibited a decrease of 14 per cent in eddy-current loss, amounting to 2 per cent of the total loss. After 250 hours the hysteresis increased one per cent at 10,000 gausses, and 2 per cent at 5,000 gausses, and yet the total loss still showed a decrease. None of the other silicon-steels showed any change in eddy currents, the slight changes in total loss being entirely due to increased hysteresis.

TABLE XII

PER CENT INCREASE IN TOTAL LOSS AT 60 CYCLES AND 10000 GAUSSES FOR DIFFERENT PERIODS OF AGING

Specimen	Time in oven					
	100 hr.	250 hr.	500 hr.	750 hr.	1000 hr.	2000 hr.
G	25	58	67	67	68	67
J	1	5	10	12	15	17
K_1		2	6	9	11	
L_1	−2	−1				
P_1		2	3	5		
Q_1	−2	−1				
R	0	0	0			
T		1	2	4		
U_1		0	0	0		
V_1		−1	0	0	1	
W		−2	−1	0	0	
X		0	0	3		

In the specimens *G* and *J* the eddy currents at first increased, but in the second thousand hours showed a marked decrease, which was sufficient to balance the steady increase in hysteresis. The result is a nearly stationary total loss. Specimen L_1 showed a slight initial decrease in hysteresis, and a later increase which was masked by decreasing eddy loss.

Specimen P_1 is a good example of the fact that the loss at different flux densities may be differently affected. The hysteresis throughout rose more rapidly at 5,000 than at 10,000 gausses, the increases amounting after 750 hours to 22 and 16 per cent respectively. This means that the law of variation of hysteresis with flux density has been changed. The exponent of B to which hysteresis is proportional has been diminished from $x = 1.66$ to $x = 1.60$. In the meantime the eddy currents have decreased, so that the increase in total loss at 10,000 gausses appears as only 5 per cent. Meanwhile, the total loss at 30 cycles and 5,000 gausses has increased 12.5 per cent. It is thus evident that an aging test should be conducted with measurements at the same flux density as that at which the material is to be used; otherwise the results may not apply to working conditions.

DISCUSSION ON "THE TESTING OF TRANSFORMER STEEL." FRONTENAC, N. Y., JUNE 28, 1909

L. T. Robinson: As the subject of iron testing has been of great interest to me for a number of years I am prompted by Dr. Lloyd's paper to ask what sort of method is this that he presents? Is it to be a standard method? Is it to be a workshop method for ordinary use, or will it necessitate the sending of samples of iron to a testing laboratory? I do not know whether there is a similarity between the methods used or not, but I believe that all users of iron have methods for testing it that have proved satisfactory. By means of one method, at any rate, with which I am quite familiar we can make an apparently satisfactory test at a labor cost of something less then 5 cents per sample.

With the advent of German activity in iron, etc., it becomes necessary to know what the results obtained in Germany mean, and we must, therefore, interpret our results by means of the Epstein apparatus. From my point of view I think it exceedingly unfortunate at this time, so long after the present methods have become well established and familiar to those most interested, that we have to consider the adoption, or the use, or the interpretation of results obtained by still another method.

Will Dr. Lloyd explain why the Epstein method is not perfectly satisfactory as a commercial standard method, and why some modification of that method, which may mean an appreciably different result, should be introduced. I believe the objections to the lack of uniform distribution of the flux in the sample are fairly well met, by the introduction, in accordance with the German specifications, of the cardboard pieces in the corners.

As to his method being accurate within one per cent, I would say that we have always been accustomed to refer our tests to ballistic measurements and from them to judge whether or not any method is a good one. Now, a question arises, is it the intention to substitute Dr. Lloyd's method for the standard method of employing a ballistic galvanometer, or does the one per cent mean that ballistic measurements have been made on these identical samples, and that the results obtained by the two methods agree within one per cent?

It seems to me that before we adopt a new method it should be demonstrated on the basis of what we have always considered to be the standard method of test, that the old method is not good and that the new one is good. Or if the new method can not be so compared, something definite should be said to convince us that what we have always considered the absolute method, namely, suitable manipulation with ballistic galvanometer, is not correct and should not be used.

V. Karapetoff: Referring to the sketch, I see the advantage over the Epstein method of assembling the strips on edge; but is not there a disadvantage in using separate corner pieces, making two joints instead of one joint as in the Epstein method? Could not a better joint be obtained by cutting the strips longer and bending them over the corner? This would do away with one of the joints, and, moreover, the joint would be made of the same material, instead of being made of a piece of iron that does not belong to the same sample.

I would also like to ask Dr. Lloyd with reference to Table XI, how he separated the hysteresis loss from the eddy-current losses? Did he assume any exponents beforehand, such as 2 for eddy currents and 1.6 for hysteresis, or did he determine the exponents experimentally from tests at different frequencies and different flux densities? As far as I am aware the values of the eddy-current loss and of the hysteresis loss are different, according to whether we assume the exponents beforehand, or determine them from the tests on the samples themselves.

C. E. Skinner: These tests have a degree of refinement rarely attempted in a commercial way, yet such refinement is necessary for the exact study of materials of this class.

After about two and one-half years' use of what is essentially the Epstein method we have found it to be the most satisfactory of any that we have tried. The insertion of bent corner pieces, as described in the paper, seems to me to be unnecessary in commercial work. The added accuracy of the corner-piece method when all necessary corrections are made, is unquestionable I think, but for commercial work the accuracy with the butt joints seems to be all that is really necessary, if inductions are kept relatively low. For inductions above 10,000 the joints may be lapped as in transformer work. We use a sample three or four times as large as that used by the authors of the paper, and the sample is of such width that material, if of satisfactory quality, can be used in commercial apparatus later, so that there is little or no actual loss of material due to the relatively large sample. While the strip is not as wide as that used by the authors we can detect little or no error from shearing provided the shear is kept sharp.

The accuracy claimed for the tests by the authors is within one per cent. I do not know the accuracy of our own method, but many checks lead me to believe it is within two per cent. On account of the ease and rapidity with which samples can be built and tested by our method I feel that it is to be preferred for commercial work where a large number of samples must be tested each day.

J. C. Lincoln: The first four samples *A*, *B*, *C*, and *D* have iron loss per pound given, and the annealed samples, which follow, have a very much decreased iron loss, sometimes as much as 50 or 60 per cent. I wish to inquire as to the method of annealing which gives this result.

Clayton H. Sharp: Is the wattmeter used in this test one of the ordinary commercial type, or is it something else? Is any special provision made to maintain the temperature of the iron constant, or to determine the temperature of the iron, and how is it done?

Andrew Pinkerton: In testing iron as it is received we usually want the result of a large part of one or more whole sheets and not of a small sample, as the user of the material is interested in the results from whole sheets and not from small samples. That is my main objection to Dr. Lloyd's method.

Clayton H. Sharp: Regarding a remark of the latest speaker, I would say that Dr. Epstein once remarked to me that he had found that any test of iron made on a small sample had no value whatever.

E. E. F. Creighton: Some years ago we made tests of samples of iron cut from large sheets, and found a great difference in the result, depending on what part of the sheet the sample was cut from. The gases in the furnace have a great effect on the annealing of the iron. I have no doubt also that small differences in the temperature affect the results.

M. G. Lloyd: In regard to Mr. Robinson's question of the method itself and the comparison with other methods: the method that we have developed, it is true, is not quite as rapid as some of the workshop methods already in use, and it is not intended that it will replace them. For factory purposes it is often sufficient to use a method which is perhaps not so accurate, but which will serve when simply comparative results are desired, to determine the uniformity of material, or something of that kind.

Regarding the results obtained, however, I wish to say that our aim was to develop a method that would give as high an accuracy as possible; in other words, to get what we might call absolute values, constants that would apply to the material, and would not depend upon any peculiarities of the method; for that reason we wanted wide strips and uniform flux densities, and some of the other conditions mentioned. It is true that the method described is very similar to the Epstein method, and yet it differs from it materially. At the Reichsanstalt in Germany the Epstein method was compared with several others by what was considered an absolute method, and it was found that on the whole the Epstein method gave very satisfactory results for the total loss at 50 cycles and 10,000 gausses, but that the separate losses due to hysteresis and eddy currents individually were not so close, that the one came high and the other low by three per cent, and that they very nearly balanced up in the total loss. Consequently, in making separations of that kind, as is desirable for many purposes, it is not safe to use a method which is so much in error. It is true the separation cannot be made with nearly the accuracy of the individual observations, because the result at one frequency is often in error in one direction and in the case of a second frequency it may be in the opposite direction, and the errors multiply in making the separation.

It probably would be desirable for the Institute to adopt some definite method which could be universally used and accepted by manufacturers and users of steel, in order that when tests are made they shall be under the same definite conditions, and consequently not lead to any disagreement as to quality or interpretation of results. I do not see any harm in the meantime, however, in developing in practice any number of methods, in order to have the best possible selection when any attempt is made to adopt some definite method.

As regards the comparison with the ballistic method, I do not think we can expect any alternating-current method to give results which will be the same as those given by a ballistic method. If we consider the different methods of taking ballistic curves—such as that known as the step-by-step method, by which we get a ballistic reading for each slight increment in flux, and a ballistic method in which a large change is made in flux from the tip of the hysteresis loop to another point—it is found that the two ballistic methods will not agree between themselves; discordant results are obtained according to the process adopted in carrying out the measurements.

Similarly with alternating-current measurements, it is still an open question whether frequency affects the value of hysteresis, if everything else remains the same. Some investigations in the past have appeared to indicate large differences, as much as 30 per cent, in the value of hysteresis, due to different frequencies. When differences in conditions produce such results, and iron is put through a hysteresis loop with alternating current, it is not fair to take any ballistic measurements and say that because the alternating-current measurement did not agree with them, that the alternating-current measurement is in error. I do not think the ballistic measurement is any criterion of the accuracy of the measurements with alternating magnetization.

The error in our method has been determined simply through a consideration of the separate sources of error and the accuracy of the instruments, and by a comparison of measurements under slight variation of conditions. When I state the accuracy as one per cent, I consider that the results, before the separation of losses, are to be depended on, that is, the constants of the material are known to that degree of accuracy.

Professor Karapetoff's comments on the joints in the corners are partly answered in the paper itself, in the part which I did not take time to dwell upon. Ordinarily, the corner pieces are of the same material as the test pieces, but we have found it is not necessary that they should be. One can get sufficiently good results for all commercial purposes by using stock corner pieces, instead of making a set of corner pieces for each specimen, and for that reason, in practice, we use them very often in that way.

The objection to the second joint does not seem to be justified by the results, because we find the difference in flux between the center and the end of the test piece to be very small indeed, and consequently any objection to the two joints at the corner is not substantiated.

The exponents have not been assumed in any case, as was intimated. The exponents are determined by obtaining values for hysteresis or eddy currents at two different flux densities, consequently derived from entirely independent measurements. The values of these two losses at any one flux density are determined by runs at two frequencies. Two observations at one flux density determine the separation of hysteresis and eddy-current losses. Then the values taken at two different densities are sufficient to determine the exponent which applies to these two particular flux densities.

In regard to the question on annealing, I may say that we have not done much of that. The specimens we have tested have in almost all cases been tested in the condition in which we received them, and the question of annealing was one of past history with us.

Dr. Sharp's question in regard to wattmeter and temperature conditions is answered in full in the paper.

As to the quantity of material, discussed by several, that is a point on which every person, I take it, must have his own opinion. Some think that the results of tests on samples are not of any value, and the test must be made on the entire material under question, and others seem to have found it satisfactory to use small test specimens. My own opinion is, that once a sufficient quantity is selected to represent a fair average of the material, if the method demands more beyond that, it is an undesirable feature of the method. The Epstein method, as usually employed, requires 10 kg. or 22 lb. of iron. What I take to be slightly better results are obtained with as small a quantity as 4 lb., and I think that is an advantage. Of course, if a person wants to test a whole sheet or larger quantities, it is easy to adapt the apparatus to the larger quantity. The question has been to find the apparatus which can be adapted to smaller quantities. With a method available for small quantities, one can always adapt it to one's own needs for large quantities.

I think I may be permitted at this time to call attention to the magnetization curves in Fig. 5. showing the wattless component of exciting current plotted against flux density for silicon-steel and ordinary steel. At low flux densities the silicon-steel is more highly permeable than the other, whereas at higher flux densities it is less so.

In regard to the effect of the higher magnetizing current, I wish to say one thing. It is of course undesirable for some reasons to allow the exciting current to run too high, and that has limited the design of transformers with this silicon-steel in one direction, that of pushing the flux density too high. It has been very generally thought, however, that the regulation of the transformer would be affected by a high magnetizing current. I wish to speak of that, because it is an error which is commonly made. Most of the formulas which we see in print for the regulation of the transformer involve magnetizing current. As a matter of fact, magnetizing current has nothing whatever to do with regulation, and any objections to high magnetizing current in transformers are not along the line of inferior regulation. The reason for that is, there is a certain voltage drop in the transformer, due to magnetizing current, but it comes in both at no load and at full load, and it can be easily shown that it does not affect the regulation.

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A SKETCH OF THE THEORY OF THE ADJUSTABLE-SPEED, SINGLE-PHASE, SHUNT INDUCTION MOTOR

BY F. CREEDY

Up to the present time comparatively little attention has been devoted to single-phase motors having shunt characteristics, as they have been completely overshadowed by the series type, on account of its utility for traction purposes. Nevertheless, these shunt-wound machines have many advantageous features and should have a considerable field of utility. A certain amount of work has been done on them by Milch in this country and by Latour, Fynn and Punga in Europe, and considerable success has been attained in compensating the machine, that is, in raising the power-factor to unity.

The object of the present paper is to discuss the variation of the speed of these machines from synchronism. The usual impression, at any rate until recently, has been that the shunt type of machine must necessarily run at a speed in the neighborhood of synchronism. This is not true; theoretically, machines can be built to run at any speed, though in practice there are difficulties in running below synchronism.

First of all, it will be as well to describe briefly the general principles on which all single-phase shunt motors work. All practical machines of this class are developments of the machine shown in Fig. 1, usually known as the Atkinson commutator induction motor. This consists of a slotted stator or primary with a uniform air-gap all round, equipped with a single distributed single-phase winding, and a drum-wound rotor fitted with a commutator, as in a direct-current machine. On the commutator rest four brushes or groups of brushes (in a two-pole machine); the axis of one " pair " of brushes usually lies parallel to that of the primary winding and that of the other perpendicular thereto, but this position is not essential. At standstill the primary coil merely induces a current on the $Y\ Y$ axis (Fig. 1) and hence there is no starting torque. But as the motor speeds up, a current is induced along the $X\ X$ axis which produces a flux along that axis. This current and the flux it produces are nearly in phase with the impressed electromotive force and hence in quadrature with the flux along $Y\ Y$. Therefore, the flux along $Y\ Y$ (the primary flux) can produce no torque in combination with the current along $X\ X$. In the neighborhood of synchronism, however, the current along $Y\ Y$, or the load current, is nearly in phase with the flux along $X\ X$; hence there will be a torque due to these two in combination.

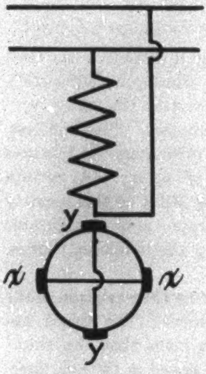


FIG. 1.

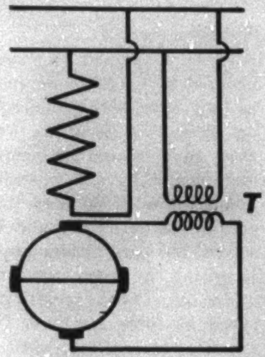


FIG. 2.

The flux along $X\ X$ may properly be regarded as the "field" flux of the motor, since it is the flux to which the torque is due. Similarly the current along $Y\ Y$ may be regarded as the armature current, since it has the same functions as this current in a direct-current machine, although, of course, it is induced from the stator, instead of being led directly in as in the continuous-current motor.

The electromotive force on the $X\ X$ axis is due to the movement of the rotor conductors through the primary flux, or flux interlinking the primary circuit. It is, therefore, directly proportional to the speed. The flux along the $X\,X$ axis, which is determined by this electromotive force in the same manner that the primary flux is determined by the primary electromotive force, is therefore also directly proportional to the speed.

Such a motor reaches its limiting speed when the counter electromotive force, which may be represented by E_2, induced by the field flux (the flux along the axis $X\,X$) in the armature circuit along the axis $Y\,Y$ balances the electromotive force E induced therein by the primary flux; or, more exactly, when the vector difference, $E - E_2$, between these two is in quadrature with E_2, the counter electromotive force. This condition is clearly the same as that which limits the speed of the direct-current shunt-wound motor. Hence it would seem that the same methods which are available for varying the speed of the latter should be available here. There are two of these methods, (1) variable voltage control and (2) adjustable field excitation. To apply the first method to the single-phase induction motor we have merely to feed an extra voltage from the line into the $Y\,Y$ axis, say by means of a transformer as shown in Fig. 2. thereby increasing E. In order that the increased electromotive force E may be balanced by E_2 the motor must clearly run at a higher speed.

It might be thought at first sight that in order to increase E it is merely necessary to increase the primary flux, say by increasing the primary impressed electromotive force. This, however, is a fallacy, because the counter electromotive force E_2 is due to the rotation of the armature in the primary field and is therefore proportional to that field. Hence any variation of the primary field simply varies E and E_2 in the same proportion and the speed consequently remains the same. One may also remark that the secondary field flux becomes effectively equal to the primary flux at synchronous speed, and hence E_2 is effectively equal to E at that speed, which is practically the free running speed of the normal motor.

The above method of speed variation was first discovered by Mr. F. Punga, in 1905 and is probably on the whole one of the most satisfactory. It was subsequently reinvented by Mr. J. Perret, Mr. V. A. Fynn, the writer and others.

A second method, suggested by the writer, is to weaken the field along the $X\,X$ axis by inserting an inductance or a capacity in the $X\,X$ circuit, as shown in Fig. 3. An inductance tends to raise the speed and a capacity to lower it. This method is precisely analogous to the speed variation of shunt-wound direct-current motors by field control, except that inductance or capacity must be used instead of resistance. The cause of this is that the circuit $X\,X$ is an almost purely inductive one, and consequently the magnetizing current which flows in it lags practically 90 degrees behind the electromotive force which produces it. It is not desired to alter the phase of the current, or of the flux it produces; hence in order to weaken it an inductance is inserted in the $X\;X$ circuit, and to strengthen it, a capacity. The use of resistance would tend to change the phase of the flux and impair the torque.

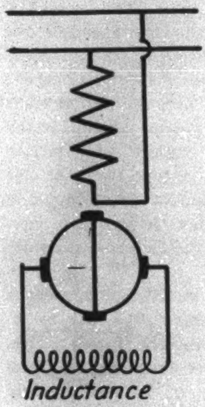


Fig. 3.

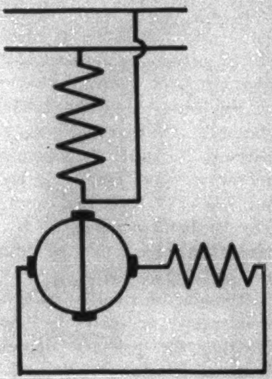


Fig. 4.

There is a third method which has no precise analogue in direct-current work. Clearly the flux necessary to balance the electromotive force E_1 induced in the $X\,X$ axis depends on the number of turns in the $X\,X$ circuit. Hence if a coil be put on the stator with its axis parallel to the $X\,X$ axis, and connected in series with the $X\,X$ brushes (see Fig. 4) it will either strengthen or weaken the flux along the $X\;X$ axis, according as the magnetomotive force of this coil opposes or assists the rotor ampere-turns.

These three methods of speed variation are the only radically distinct methods which may be applied to the single-phase induction motor pure and simple. They may, of course, be combined with each other, and with methods of phase compensation and of obtaining a starting torque, in an almost unlimited number of ways, as Messrs. Punga and Fynn have shown in their patent specifications dealing with the subject. Mr. Fynn has also invented a conductive type of machine in which the rotor circuit along the $Y\ Y$ axis is provided with a neutralizing coil, there being along the same axis a coil in shunt to the line, the sole purpose of which is to provide a flux capable of inducing an electromotive force on the $X\ X$ axis. He has also described a number of types in which the $X\ X$ axis is excited by means of a phase transformer, there being only one pair of brushes per pair of poles, but these types of machine do not come within the scope of the present discussion, which is confined to induction types.

Before deciding whether these methods of speed variation are really feasible and, if so, which is the most satisfactory, one must investigate the theory of the subject, as the introduction of the various voltages, etc.. might so disturb the phase relations that some or all of the methods might be almost useless.

The clearest manner of describing the properties of an alternating-current motor is usually by means of the circle diagram. It is proposed, therefore, to describe the circle diagrams of the three types of motor described above, and to compare them with the well-known diagram of the ordinary single-phase induction motor.

It will be found that the deduction of these diagrams is quite complicated, as the properties of the motors seem to depend largely upon secondary reactions, which accordingly have to be taken fully into account. The most convenient way to calculate the position of the current circle is to determine three points upon it corresponding to three different speeds.

Discussing the motors in the order given above, the first thing we may remark is that if the electromotive force induced by the primary flux in the $Y\ Y$ axis be E volts and an electromotive force, E_s be introduced, say, by a transformer, the increase of speed will *not* be in the ratio $\frac{E+E_s}{E}$, as it would be in a direct-current motor, because the field flux of the motor is directly proportional to the speed instead of being constant. The change in speed therefore will be proportional to $\sqrt{\frac{E+E_8}{E}}$.

In the deduction of the circle diagram, the three most convenient points to take are (1) standstill, (2) synchronous speed and (3) the free running speed. The currents corresponding to these three speeds must be deduced.

The deduction of the current at standstill presents no difficulty. If I_0 = magnetizing current of the machine or the current which the primary winding would take if the secondary were entirely open-circuited, and if I_s = standstill current, then

$$I_s = \frac{I_0}{\sigma},$$

σ being the dispersion coefficient.

The deduction of the other two currents is not so simple. Let E be the electromotive force induced by the primary flux on the $Y\ Y$ axis. Then on the $X\ X$ axis, at a speed k times synchronous speed, there will be an electromotive force k times as great and in quadrature with E; call this E_1. The electromotive force E_1 produces on the $X\ X$ axis a current I_2 proportional to itself. To this current the cross flux is due, and the electromotive force induced by this cross flux on the $X\ X$ axis or, in other words, the electromotive force of self-induction due to this current, is represented in Fig. 5 as $I_2\,X$. This cross-flux produces, in its turn, owing to the revolution of the rotor, a back electromotive force on the $Y\ Y$ axis, which again will be k times as great as E_1. This opposes E and is the counter electromotive force of the motor. This is shown in the diagram (Fig. 5) as E_2. The resultant of E and E_2, shown as E_3, is the electromotive force which causes the current to flow through the local impedance of the $Y\ Y$ circuit. The object in drawing this diagram is to get at the electromotive force E_3. The magnitude of this electromotive force may be deduced more conveniently, however, by means of the simplified form of diagram due to Mr. Punga, shown in Fig. 6. First set out $\overline{O\ E}$ as shown, and then cut off from E a length k times as great to represent E_1. This will be in quadrature with the true E_1 but will serve for the present purpose. Draw in $\overline{E_1\ A}$ equal to $I_2\,R$ and $\overline{O\ A}$ equal to $I_2\,X$, as before. Cut off from $\overline{O\ A}$ a length k times as great to represent E_2. This vector will have the correct phase relation, as may be seen by reference to Fig. 5, though it is shown for convenience with the opposite direction. Consequently, the electromotive force, E_3, is simply the vector difference between E and E_2. If the phase difference between E and E_2 were neglected, E_3 would be equal to $(1-k^2)\,E$, since $E_1 = k\,E$ and $E_2 = k\,E_1 = k^2\,E$.

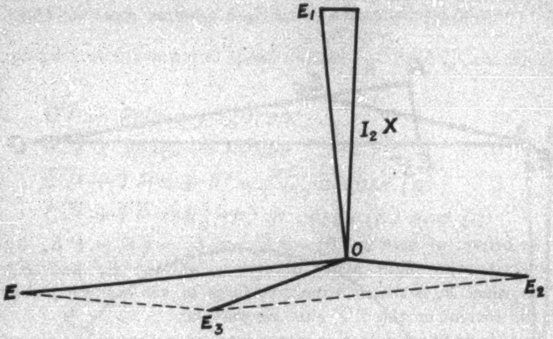


Fig. 5.

The action described above, however, is not the only one taking place. In addition to the main flux interlinking both primary and secondary along the $Y\ Y$ axis, there is the secondary leakage flux proportional to the current along $Y\ Y$, and interlinking the secondary only. Clearly all the arguments which apply to the main flux must also apply to this secondary flux. Hence, a diagram may be drawn representing the effects of the leakage flux which will be precisely similar to the one of Fig. 6 Set out E_4, Fig. 7, to represent the electromotive force of self-induction along the $Y\ Y$ axis. Then the flux to which this is due will induce an electromotive force E_5 on the $X\ X$ axis k

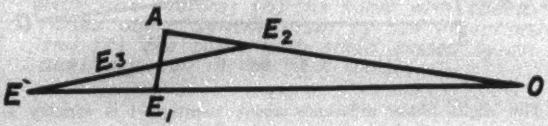


Fig. 6.

times as great. Using the same convention as before, cut off from E_4 a length k times as great to represent this. The electromotive force, E_5, on the $X X$ axis will be balanced, as before, by a small supplementary current flowing on that axis, and producing a supplementary flux k times as great as that to which E_4 is due; $O A'$ is the electromotive force induced on the $X X$ axis by this flux. The same flux will induce on the $Y Y$ axis an electromotive force, E_6, k times as great as $O A'$.

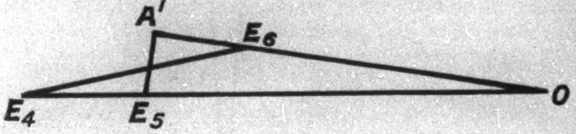


FIG. 7.

As before, we may say $E_5 = k E_4$ and $E_6 = k E_5 = k^2 E_4$, by neglecting the slight phase difference between E_4 and E_6. Then, since E_4 is the electromotive force of self-induction due to the current on the $Y Y$ axis, we may say:

In a single-phase induction motor running at a speed of k times synchronism, the electromotive force of self-induction due to a given current along the primary axis will have $(1 - k^2)$ times its value at standstill.

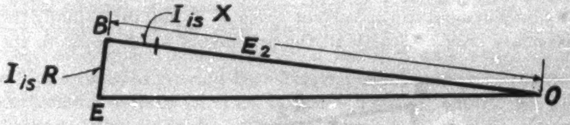


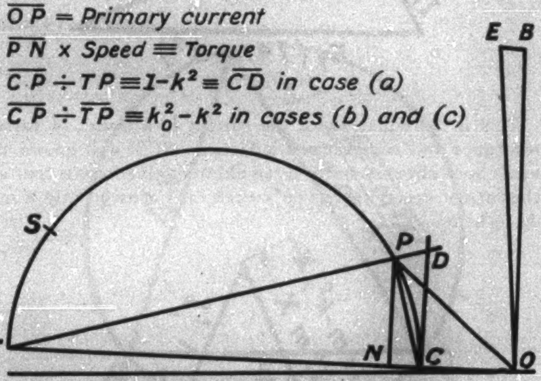
FIG. 8.

The slight phase difference above mentioned is strictly a second order effect and will be neglected in future.

In the polyphase induction motor it is well known that the rotor self-induction decreases with increasing speed, owing to the decrease in the frequency. The above investigation shows that a similar effect takes place in the single-phase motor.

With the aid of the foregoing diagrams it is not difficult to establish the circle diagram for the single-phase induction motor. Draw first the triangle of electromotive forces corresponding to synchronous speed (Fig. 8). Here $\overline{OE}$ is, as before, the electromotive force induced by the primary flux and $\overline{OB}$ is equal to the counter electromotive force E_2 at synchronism.

The impedance of the circuit is $\sqrt{R^2+(1-k^2)^2X^2}$, as shown by the subsidiary diagram. At synchronism, then, when $k = 1$, the reactance vanishes. At any other speed, the current I_1 on the $Y\,Y$ axis may be resolved into two components, I_{1s}, the current at synchronous speed (equals $\frac{\overline{EB}}{R}$) and I_1', the remaining or load current; the first component may be considered present at all speeds. $\overline{OE}$ is also always present. Now $\overline{OE}+\overline{EB} = \overline{OB}$, and $\overline{OE_2} = \overline{OB}\times k^2$. Hence the resultant of $\overline{OE}$, $\overline{EB}$, and $\overline{OE_2}$ is $\overline{E_2B} = (1-k^2)\times\overline{OB}$, as may be easily seen.


$\overline{OP}$ = Primary current
$\overline{PN}$ x Speed ≡ Torque
$\overline{CP} \div TP \equiv 1-k^2 \equiv \overline{CD}$ in case (a)
$\overline{CP} \div \overline{TP} \equiv k_0^2-k^2$ in cases (b) and (c)
E
B
S
P
D
T
N
C
O

Circle - Diagram of (a) the single phase induction motors; (b) the same with speed raised above synchronism by self induction, and (c) the same with speed raised by an auxiliary coil in the X X axis.

FIG. 9.

Besides this we have $I_{1s}X(1-k^2)$ in quadrature with I_{1s}, that is, with $\overline{EB}$, and opposite in phase to $\overline{OB}$; this is a constant quantity at a given speed; $I_1'R$; $I_1'X(1-k^2)$.

The resultant electromotive force, then, which may be regarded as producing the flow of the current is $(\overline{OB}-I_{1s}X)(1-k^2)$ which may be called $E_r(1-k^2)$.

Hence,

$$I_1' = \frac{E_7\,(1-k^2)}{\sqrt{R^2+(1-k^2)^2\,X^2}} = \frac{E_7}{\sqrt{\left(\frac{R}{1-k^2}\right)^2+X^2}}$$

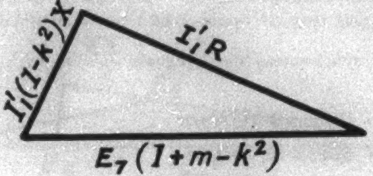


FIG. 10.

This is the equation for the current in a circuit of variable resistance and constant self-induction. It is well known that under such circumstances, if the electromotive force is constant, the current vector travels on a circle, and consequently it must do so here.

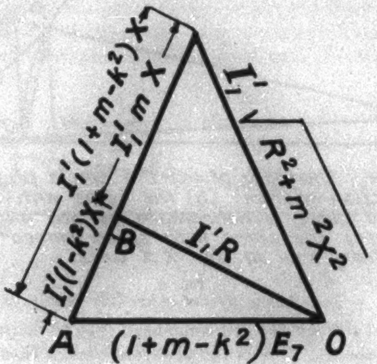


FIG. 11.

Fig. 9 shows the complete diagram, the electromotive force triangle *O E B* being shown vertical so as to bring the circle into a more customary place.

From the foregoing it is easy to investigate the value of I_1' in the variable-speed motor, as I_1, will be the same as before.

There is now another electromotive force $E_8 = m\,E_7$. Assuming that it is in phase with E_7, we get $(1+m-k^2)\,E_7$ for the resultant electromotive force causing the current to flow. The three sides of the triangle of electromotive forces will then be as indicated by Fig. 10.

To prove that I_1' still moves on a circle, $I_1'\,(1-k^2)\,X$ may be written $I_1'\,(1+m-k^2)\,X - I_1'\,m\,X$, and this results in the diagram Fig. 11, which is self-explanatory.

Since the angle $\overline{O\,B\,C}$ is a right angle, $\tan\theta = \dfrac{R}{m\,X}$ and hence θ is constant.

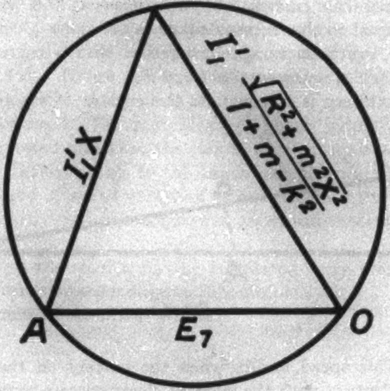


FIG. 12.

Since both $\overline{O\,A}$ and $\overline{A\,C}$ contain as a factor the quantity $(1+m-k^2)$, dividing all three sides by this will give the somewhat simpler values of Fig. 12.

Since $\overline{O\,A}$ and θ are constant while the ratio

$$\frac{\overline{A\,C}}{\overline{O\,C}} = \frac{(1+m-k^2)\,X}{\sqrt{R^2+(m\,X)^2}},$$

and therefore varies with the speed, it is clear that the point C must describe a circle. Since $\overline{O\,C}$ is proportional to the load current, it is evident that in the motor under consideration the secondary current vector moves on a circle.

The magnitude of the load current I_1' is given, at any speed, by the equation

$$I_1' = \frac{E_7\,(1+m-k^2)}{\sqrt{R^2+(1-k^2)^2\,X^2}}$$

and when $k = 1$, then $I_1' = \frac{m\,E_7}{R}$; or, at synchronous speed the secondary load current is equal to the electromotive force fed in through the commutator, divided by the secondary resistance. The current at synchronism in this motor, therefore, is equal to the current taken by a single-phase induction motor at synchronous speed, together with a current E_8/R in phase with the electromotive force E_8.

The next step is to calculate the current at the free running speed. This speed occurs when the current on the $Y\,Y$ axis is in quadrature with the counter electromotive force E_2.

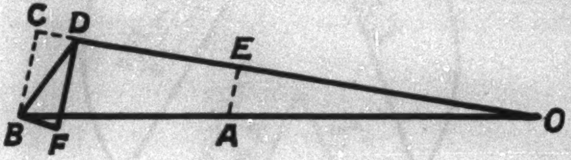


FIG. 13.

Fig. 13 is a new diagram in which $\overline{O\,A} = E$, the electromotive force induced on the $Y\,Y$ axis by the primary flux. Then the triangle $O\,A\,E$ represents the conditions at synchronous speed. This triangle, as shown above, is identical with the electromotive force triangle for the $X\,X$ axis, and hence $\overline{A\,E}$ is equal to $I_2\,R$ and is in quadrature with $\overline{O\,E}$. If, however, an electromotive force $\overline{A\,B}$ be added, making a total of $\overline{O\,B}$, then, at a suitable speed, the counter electromotive force of the motor will rise to $\overline{O\,C}$, and $\overline{B\,C}$ will equal $\frac{\overline{O\,B}}{\overline{O\,A}} \times \overline{A\,E} = k^2.\ \overline{A\,E}$, since the speed is only proportional to the square root of the voltage. But it is only at synchronism that the rotor current is in phase with the vector difference between the impressed and the counter electromotive forces. At the speed now under consideration the self-induction along the $Y\,Y$ axis comes into play. We saw that at the speed $k \times$ synchronism the inductance along this axis was $(1 - k^2)\,X$, if X is its value at standstill. Above synchronism, accordingly, it will be negative, or in other words, have the effect of a capacity. Hence in the diagram Fig. 13, in which $\overline{B\,D}$ is the vector difference between the impressed and the counter electromotive forces, $\overline{D\,F} = I_1\,R$ and $\overline{B\,F} = (1 - k^2)\,I_1\,X$.

If this diagram is to correspond to the free speed, $\overline{D\,F}$ must be perpendicular to $\overline{O\,D}$, since it is in phase with I_1, and in order that the torque may vanish I_1 must be in quadrature with $\overline{O\,D}$; $\overline{B\,F}$ is perpendicular to $\overline{D\,F}$ and therefore must be parallel to $\overline{O\,D}$; $\overline{B\,C}$, as shown above, is also perpendicular to $\overline{O\,D}$. Hence $B\,C\,D\,F$ is a parallelogram and $I_1\,R = \overline{D\,F} = \overline{B\,C} = k^2\,\overline{A\,E}$. Hence the secondary current on the $Y\,Y$ axis at the free speed has the same phase and is k^2 times as great as at synchronism in the normal single-phase induction motor. It may be noted also that the motor does not quite attain the free speed corresponding to the impressed electromotive force. If this method of speed variation is used to lower the speed, the motor evidently will rise somewhat above its theoretical speed on no load.

To sum up the results, having calculated three points on the circle diagram corresponding to this motor:

The current at standstill will be

$$I_s = \frac{I_0}{\sigma}$$

where I_0 = magnetizing current of the machine or the current which the primary would take if the secondary were entirely open-circuited, and σ = dispersion coefficient.

The current at synchronous speed $= 2\,I_0 + \dfrac{E_s}{R}$. The magnetizing current I_0, of course, lags nearly 90 degrees behind the impressed electromotive force e while $\dfrac{E_s}{R}$ is in phase with it; therefore the addition must be made vectorially.

The secondary current at the free speed was $k^2\,I_0$, and adding the primary magnetizing current, the primary current at the free speed $= (1 + k^2)\,I_0$.

Fig. 14 shows the circle diagram drawn through the three points calculated; here $\overline{O A}$ is the standstill current, $\overline{O B}$ that at synchronous speed, and $\overline{O C}$ that at the free speed, $\overline{D P}$ being the secondary current.

The torque will clearly be proportional to the product of the secondary current $\overline{D P}$ and the flux along the $X X$ axis, multiplied by the cosine of the angle between them. This flux, like the counter electromotive force, is nearly in phase with the primary electromotive force, differing from it by a small angle due to the secondary resistance. It is shown in the diagram as $\overline{O F}$ and is, of course,proportional to the speed. Hence if a line $\overline{D G}$ be drawn perpendicular to $\overline{O F}$ and passing through $\overline{O D}$, we may say that the torque is proportional to $\overline{P N} \times K$, the same construction as in the ordinary single-phase induction motor.

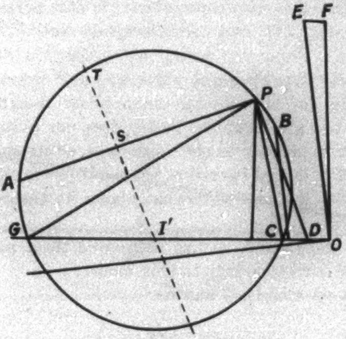


FIG. 14.

It is easy to show, morever, that $\overline{C P} \div \overline{A P}$ is approximately equal to $k_0^2 - k^2$ where k_0 is the free running speed ÷ synchronous speed.

By setting out a line $\overline{S T}$ so that the angle $A R T$ is equal to $A P C$, we get $k_0^2 - k^2$ as the intercept $\overline{Q R}$ cut off on this line by the line $\overline{A P}$. $\overline{S T}$ will naturally be parallel to the tangent to the circle at C.

This is all we need know of the diagram in order to appreciate the characteristics of the motor.

Fig. 15 gives diagrams of three methods of connecting a commutator motor: (*a*) as a plain single-phase commutator induction motor with two pairs of short-circuited brushes; (*b*) as a single-phase induction motor with the speed raised above synchronism by Punga's method; (*c*) as a two-phase induction motor with two pairs of brushes short-circuited.

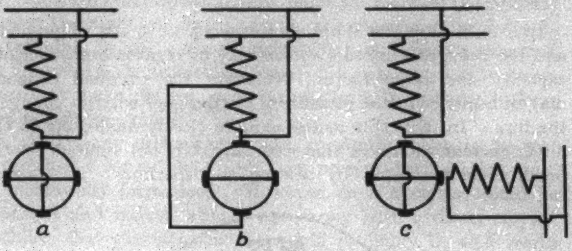


FIG. 15.

In Fig. 16, 1 is the well-known circle diagram of the single-phase induction motor; 2 is the better-known diagram of the two-phase motor, drawn out so that the current vector represents the total current; that is, the arithmetical sum of the currents in the two phases. This is the only fair way of making a comparison. Under these circumstances the total no-load current of the polyphase motor will be the same as that of the single-phase machine, but the total short-circuit current will be doubled, giving the

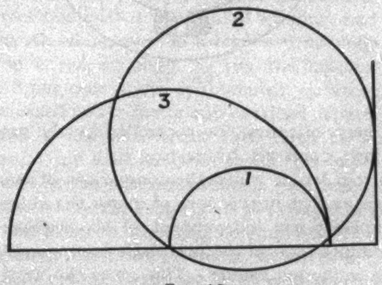


FIG. 16.

diagram as shown. Diagram 3 is the circle diagram of the new motor. The no-load current is rather greater than that of the single-phase motor, while the short-circuit current is the same. The current at synchronous speed, $\frac{E_s}{R}$, is shown in the diagram.

It is clear that the shunt motor excels both the single-phase and the polyphase motors enormously as regards both overload capacity and power-factor. Moreover the overload capacity may be adjusted at the pleasure of the designer without changing the flux. In fact, this motor is more closely analogous to the direct-current motor in that the output is not limited by the break-down point but by heating and sparking. The power-factor also may, of course, be controlled by the same means as the break-down point viz. by varying E_b.

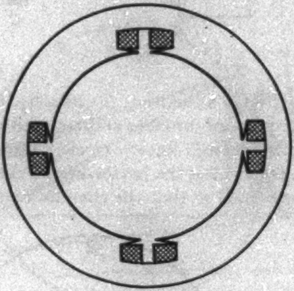


FIG. 17.

The principal lesson which the comparison of circle diagrams teaches, then, is that in this type of motor the power-factor and overload capacity are independent of the leakage coefficient, which determines both in the polyphase motor and the ordinary single-phase induction motor. This gives the designer a great deal of freedom in the choice of the number of slots, air-gap, etc. In fact, in the writer's opinion, it is probable that a motor of this type might be made to operate fairly well if built with salient poles, somewhat as shown in Fig. 17. Such a motor, no doubt, would be somewhat heavier than the usual distributed-winding type, and would probably encounter a good deal of prejudice at first. The dispersion coefficient would undoubtedly be very high, say 0.25, but, as already shown, this affects neither the overload capacity nor the power-factor.

It is true that the theory given above does not take account of the primary leakage in detail, but it may be pointed out that if the primary current leads, then the electromotive force of self-induction due to this current tends to increase the primary counter electromotive force; that is, the electromotive force to be balanced by the main or air-gap flux will be greater than the impressed electromotive force. It can very easily be arranged to make the primary current lead, so primary leakage need not cause trouble.

A good many difficulties would, no doubt, have to be met before such a radical departure from present-day practice could be successfully introduced. However, such a motor would be so simple and robust, almost comparing with a direct-current machine, that the introduction would probably be well worth the effort. It would also present possibilities of standardization probably excelling those offered by any other type. To adapt a given frame for different speeds, frequencies (within limits), voltages or horse-powers (also within limits), all one has to do is to change the coils, since the armature is standard, not being connected to the mains, and the speed can be changed without changing the number of stator poles. However, the salient-pole machine is at present a speculation, as one naturally would try a machine with a distributed winding, first it would probably be worth while, even in a standard machine in which speed variation is not required, to run the machine at, say, 7 per cent or 8 per cent above synchronism on account of the very much increased power-factor and overload capacity thereby obtained. Such a machine would then drop to about synchronous speed at full load, and one should get improved commutation as well as the other advantages mentioned. All this holds in the case where the motor runs above synchronism.

If this method of speed variation be employed to reduce the speed, very different results are obtained. In this case, the electromotive force E_v is reversed, and the circle is as shown in Fig. 18, where $\overline{OC}$ = no load current, $\overline{OA}$ = short-circuit current, and $\overline{OB}$ = current at synchronous speed. In this diagram the motor part (that above $\overline{AC}$) almost disappears. Hence the machine will not carry any load, and the conclusion is that this method is not suited for reducing the speed below synchronism.

THE USE OF SELF-INDUCTION

We now come to the second type of motor in which the speed is varied by inserting self-induction in the " field " or X X circuit. A simple modification of the diagram used before will serve to elucidate the properties of this type of motor. In this diagram (Fig. 19) we have E as before, but the speed is now above synchronism. Hence E_1, the voltage on the X X axis, will be greater than E, as shown. This electromotive force is balanced, as before, by $I_2 R$ and $I_2 (X_1+X_0+X)$, R being the secondary resistance and X_0+X+X_1 the total secondary reactance. This must now be divided into two parts, the reactance X_0+X, due to the flux along X X and the reactance X_1 which is external to the motor. The counter electromotive force E_2 will, of course, be k times $I_2 (X_0+X)$ only. This is shown in the diagram, and the free speed will occur as before when the current on the Y Y axis is in quadrature with E_2.

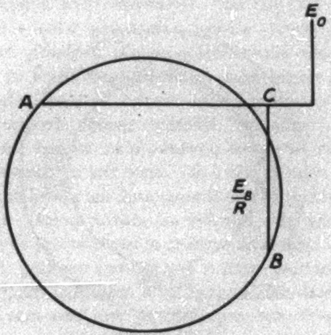


FIG. 18.

Now, following through the various reactions due to the leakage flux along the Y Y axis in exactly the same way as before, a diagram quite similar to Fig. 19 may be derived and it will be found that the reactance is balanced exactly at the free speed of the motor. Hence the current on the Y Y axis must be in phase with the vector difference between E and E_2 at that speed. Thus the relations of transformer electromotive force, counter electromotive force, and current on the Y Y axis are just the same in the new motor at its free speed, as in the ordinary single-phase induction motor. The current, therefore, will have the same value; that is, the current on the $Y\ Y$ axis will be equal to that which exists on the $X\ X$ axis at synchronous speed. The diagram then is identical with that of the single-phase induction motor save that the free speed is different.

If k_0 be the ratio of free speed to synchronous speed, then the construction which in the ordinary motor gives $(1-k^2)$ will give $(k_0^2-k^2)$. The torque characteristics, overload capacity, etc., will be just as in the ordinary induction motor. Hence this machine will work best when compensated.

A capacity connected across the $X\ X$ circuit would clearly be just as effective in lowering the speed, but it is not much use going into the theory of this in detail, as the condenser required for such a method of speed regulation would be far too costly for practical use.

One caution is very important when testing these motors, or, indeed, any type of commutator induction motor. The presence of four brushes on the commutator, opposite pairs being joined together, gives an opportunity for the circuit along $X\ X$ to differ in resistance from that along $Y\ Y$. If the $X\ X$ circuit has a high resistance, say, double that of the $Y\ Y$ circuit, then the difference between E and E_1 at synchronous speed will be double what it would be if the two resistances were equal; hence the no-load current on the $Y\ Y$ axis will be doubled and the power-factor of the motor correspondingly reduced. It is very important, therefore, to keep the resistance of the $X\ X$ circuit down, or very unfavorable conclusions may be drawn as to the power-factor of these machines.

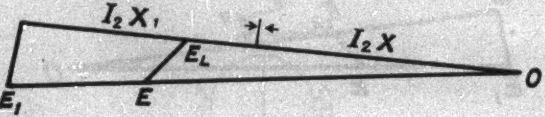


FIG. 19.

We now come to the third type of motor, in which there is a coil parallel to the $X\ X$ circuit and connected in series therewith. Fig. 20 is the diagram for this case; it is quite similar to those already drawn. The voltage E_1 is larger than E, as before, because the speed is assumed to be greater than synchronism. This is balanced by $\overline{O\ E}$, the electromotive force of self-induction due to the flux along $X X$ interlinking the whole circuit along that axis, both on the stator and the rotor. $\overline{O E''}$ is the electromotive force induced by the field flux in that portion of the $X X$ circuit which lies on the armature alone; of course, $\frac{E''}{E'} = \frac{T}{T_1}$, if T is the number of turns on the armature and T_1 that on the armature and auxiliary coil combined. The counter electromotive force, E_2, will be k times E''. The free speed occurs as before when $E - E_2$ is perpendicular to E_2.

An examination of the subsidiary diagram for the leakage flux will show that the self-induction in the $Y Y$ axis is also balanced at the free speed, since the diagram is identical with the one just given. Hence, as in the last type of motor considered, the current on the $Y Y$ axis at the free speed is equal to the stator magnetizing current, and, consequently, the stator no-load current is equal to double this latter, just as in the ordinary single-phase induction motor. The circle diagram also is identical with that of the induction motor, as with the last type discussed, save that the speed construction gives $(k_0^2 - k^2)$ instead of $(1 - k^2)$.

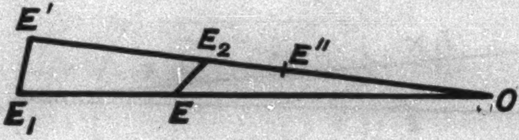


FIG. 20.

The present method supplies probably the best method of lowering the speed, but its scope is limited by the following considerations.

Suppose it is desired to reduce the speed of a motor to half of the synchronous speed. In order to do this, the "field" flux must be twice that at synchronous speed. But in order to get twice the flux in the $X X$ axis, one-half the number of turns would be required, even if the voltage induced in the $X X$ circuit remained constant at all speeds. Since it is halved at half speed, only one-quarter of the number of turns required at synchronism will be needed to give double the flux, and since the required ampere-turns are twice those at synchronism, the current must be eight times that at synchronism. The current in the $X\,X$ axis is proportional to the inverse cube of the speed. The decrease of speed obtainable by this method is limited, therefore, by the abnormal increase in the current on the $X\,X$ axis.

Unless the $X\,X$ brush gear is specially designed, probably a drop of 20 per cent in speed, which will double the current on the $X\,X$ axis, is as much as will be possible.

The foregoing investigation indicates that there is no thoroughly practical method of lowering the speed, although there are several good ways of raising it.

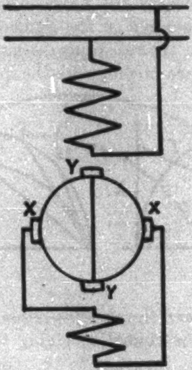


FIG. 21.

Before leaving the theory of these motors, it will be convenient to consider briefly the theory of phase compensation as applied to the single-phase induction motor, since in many cases phase compensation produces a great improvement. A diagram of connections of a compensated motor is shown in Fig. 21.

In order to avoid constructing an entirely new theory of this motor, the best way to consider it will be as follows: Add along the $X\,X$ axis an electromotive force, E_0^1, of constant value and in phase with the impressed electromotive force. Here E'_0 may be regarded as superposed on the others and as producing its own effects undisturbed by any of the other actions going on in the motor. This will give rise on the $Y\,Y$ axis to another electromotive force in quadrature with it and proportional to the speed, and this second electromotive force will lead E' by 90 degrees if the compensating coil be correctly connected. The current due to this electromotive force will be determined by the resistance and inductance of the $Y\ Y$ circuit in the usual manner; in fact, this current will be

$$I_3 = \frac{k\,E_c^1}{\sqrt{R^2 + (1-k^2)^2\,X^2}}.$$

It is easily proved that if a constant electromotive force be applied to a circuit of constant resistance and variable self-induction, the current vector will move on a circle, as in Fig. 22. If it were not for the factor k in the numerator, I_3 would clearly flow in such a circuit, the resistance being R and the inductance $(1-k^2)\ X$, and therefore varying with the speed, but in the present case the values obtained from such a circle have to be multiplied by k as shown by the equation, giving the diagram shown in Fig. 23. This current then has to be added to the ordinary induction-motor current to obtain the current in the compensated motor, and the diagram of Fig. 24 is obtained. The very simple theory on which this diagram is based is also the basis of the treatment of the ordinary single-phase induction motor and will be found in accord with the more complex theories which have been published from time to time, in which the compensated motor is treated independently.

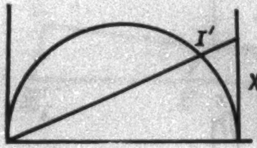


FIG. 22.

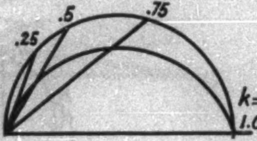


FIG. 23.

The very considerable increase in the overload capacity is clearly shown by Fig. 24; it usually amounts to about 40 per cent. The locus of the current vector is now not strictly a circle, but for the purpose of calculating the overload capacity it may conveniently be assumed to be such.

In order to get satisfactory compensation, there must be a current on the $Y\ Y$ axis at synchronism capable of producing a flux along that axis sufficient to balance the primary electromotive force, thereby rendering the primary magnetizing current unnecessary; therefore, the normal current on the $Y\,Y$ axis must be reversed, and in order to do this, a current of twice the magnitude and of opposite direction must be superposed on it.

At synchronism the compensating current on the $Y\,Y$ axis is $\frac{E^1}{R^1}$, as shown above, E^1 being the compensating electromotive force. For good compensation, $\frac{E^1}{R} = 2\,I_0$, or $E^1 = 2\,I_0\,R$. This furnishes a means of getting an idea of what the compensating electromotive force should be, but the best value can really only be found by experience.

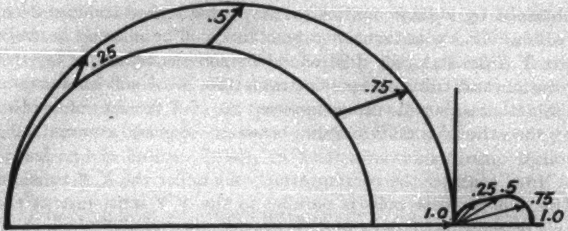


FIG. 24.

COMMUTATION

The commutation of the various types of motor described above must be discussed before one can decide that they are entirely feasible. Consider first the commutating coils under the $Y\,Y$ brushes. There will be three electromotive forces induced in these: the reactance voltage, proportional to and in phase with the current; the "electromotive force of rotation" or that induced by the commutating coil cutting the flux along the $Y\,Y$ axis, and the "transformer electromotive force" or electromotive force induced by the alternation of the flux along the $X\,X$ axis, which flux clearly threads the commutating coil. The flux along the $Y\,Y$ axis also induces an electromotive force of rotation on the $X\,X$ axis similar to that induced in the commutating coil. This electromotive force, obviously, will differ from thatc induced in the commutating coil merely by the ratio of transformation between the rotor and the commutating coil.

The flux along the *X X* axis induces a similar transformer electromotive force in the *X X* circuit, likewise differing from that induced in the commutating coil merely by the transformation ratio. The two electromotive forces induced in the *X X* circuit balance one another at every speed, of course, and it therefore follows that the similar electromotive forces induced in the commutating coil do so also. This leaves only the reactance voltage, which exists also in the direct-current machine.

We may, therefore, say that as long as the *X X* brushes remain short-circuited, the commutation under the *Y Y* brushes is the same as that of a direct-current machine. Now the *Y Y* brushes carry the main current while the *X X* brushes only carry a small magnetizing current, so that when speed variation is obtained by voltage control we may expect good commutation. If, however, extra turns or a reactance coil be inserted between the *X X* brushes, the difference between electromotive force of rotation and transformer electromotive force will be equal to the actual external voltage between the *X X* brushes multiplied by the ratio of transformation between rotor and commutating coil.

Now, consider the commutating coils under the *X X* brushes. The axis of these coils is parallel to the *Y Y* axis, just as the axis of the coils under the *Y Y* brushes was parallel to the *X X* axis. The " electromotive force of rotation " and transformer electromotive force induced in these coils then correspond to the induced and counter electromotive force, E and E_2, discussed above. These, we saw approximately balanced one another at the free speed in the simple induction motor. Hence, it may be considered that in the simple commutator induction motor, the commutation under the *X X* brushes is like that of a direct-current motor at and about the free speed. If, however, an external electromotive force, E_8 be inserted in the *Y Y* axis, say, such as to increase the induced electromotive force. E, then the counter electromotive force $E_2 = E + E_8$ or $E_2 - E = E_8$. As before, the resultant of the transformer and rotation electromotive force in the commutating coil on the *X X* axis is equal to $E_2 - E = E_8$ multiplied by the transformation ratio between the rotor and the commutating coil. We may, therefore, generalize from the statement made above as follows:

The resultant induced electromotive force (excluding reactance voltage) in the commutating coils under two opposite brushes of a commutator induction motor is equal, near the free speed, to the electromotive force between the alternate pair of brushes multiplied by the transformation ratio between the rotor and the commutating coil; hence, a potential difference between any two opposite brushes will tend to make the alternate pair spark. To obtain a given rise of speed, therefore, with the least sparking voltage, one should have equal potential differences between both pairs of brushes.

The foregoing theory cannot claim any great elegance or high degree of perfection. It represents merely the writer's attempt to get a clear understanding of this type of motor so as to be able to design it with some certainty, and it is hoped will be received as such.

Experimental Results

A considerable amount of experimental work has already been done on adjustable-speed single-phase motors, both in this country and abroad, and there can be little doubt, I think, that a commercial machine will shortly be placed on the market either in Europe or here, or perhaps both. I propose to describe herein a number of tests which are at present at my disposal and to indicate briefly in what directions further tests are desirable.

Experiments of Mr. F. Punga and the Author

Motor No. 1. The first motor built was a small machine giving 1.25 horse-power on a circuit of 40 cycles and 220 volts. It was arranged as shown in the diagram, Fig. 4, having a cross winding divided into two parts so that three speeds were available; viz., synchronism and two speeds above synchronism. A compensating coil was also employed on this motor. The results of the tests on this machine for the three different speeds are shown in Fig. 25. It will be evident that the power-factor is very high, the slip from no load to full load considerable, and the efficiency comparatively low although tolerably good for so small a motor of this type. Constant compensation was employed at all speeds and, as the charts show, the power-factor remained very nearly constant, falling off slightly at the higher speeds. The commutation was thoroughly satisfactory at all speeds as, of course, it should be in so small a motor.

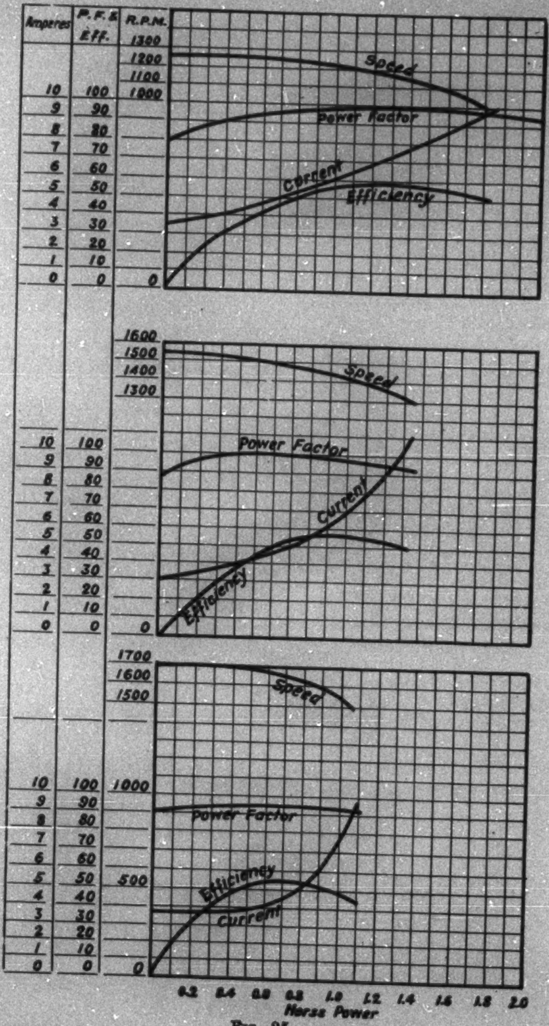

Amperes
P.F. & Eff.
R.P.M.
1300
1200
1100
1000
10 100
9 90
8 80
7 70
6 60
5 50
4 40
3 30
2 20
1 10
0 0 0
Speed
Power Factor
Current
Efficiency
1600
1500
1400
1300
Speed
Power Factor
Current
Efficiency
1700
1600
1500
1000
500
Speed
Power Factor
Efficiency
Current
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
Horse Power

FIG. 25.

Below synchronism satisfactory results were not obtained, as a totally different compensating voltage would have been required. This could not be conveniently arranged for experimentally at the time. The results obtained by Dr. Alfred Fraenckel, however, given below, show that a considerable reduction in speed below synchronism is possible by suitable arrangements. In fact, his results below synchronism are superior to any that I have yet been able to obtain.

The results obtained on motor No. 1 were considered sufficiently satisfactory to justify further experiment and one or two motors were even built commercially for driving small printing presses and the like. These had a speed range of about 1.5 to 1.0 and a capacity about the same as that of the experimental motor.

Motor No. 2. This was a 5 horse-power machine operating at 200 volts and 50 cycles. It was arranged to obtain some data on the method of varying the speed by the use of self-induction. Some speed curves on this motor are given in Fig. 26. It was found that the use of inductance in the field circuit diminished the power-factor; hence variable compensation should be arranged for when it is desired to adjust the speed of a motor by this means.

The commutation of this motor was satisfactory at all loads and speeds, but the full-load efficiency averaged only 63 per cent to 65 per cent. The slip between no load and full load was high.

In spite of the comparatively poor results of tests on this motor the writer believes that the use of inductance in conjunction with a small adjustable compensating transformer offers one of the most promising means of varying the speed at our disposal. The two may be combined so that movement of the lever of the field-regulating controller simultaneously varies the inductance and adjusts the compensation. In this case the controller will be hardly more complicated than the regulating rheostat of a direct-current motor.

Motor No. 3. On this third motor a considerable number of tests have been made. This was a four-pole machine operating at 400 volts and 25 cycles. Arrangements were made for adjustable compensation in case it was needed, but it was finally found that very satisfactory results could be obtained without it. Arrangements were also made to try the method of speed variation both by armature voltage control and by field variation. The curves in Fig. 27 show the different speed curves, and those in Fig. 28 the power-factor at one-half, three-quarters and full load. A very wide speed range was covered, *viz.*, about 2½ to 1 and it may be noted that the high slip characteristic of the older motors has been eliminated.

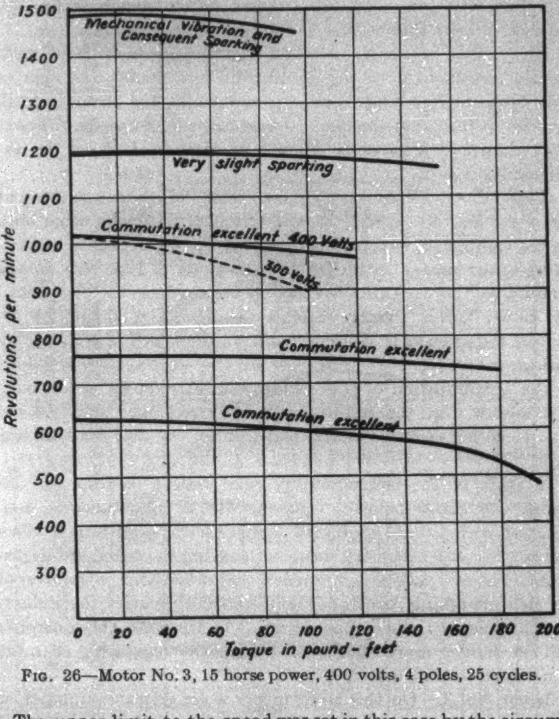


FIG. 26—Motor No. 3, 15 horse power, 400 volts, 4 poles, 25 cycles.

The upper limit to the speed was set in this case by the circumferential speed of the commutator, which, above 1400 rev. per min., gave rise to a good deal of vibration and consequent sparking. The lower limit was due to the abnormal increase of the current in the cross or magnetizing brushes which, below about 600 rev. per min., began to give rise to excessive heating and severe sparking under these brushes. A further reduction of the speed was also impracticable for another reason. Below synchronism the ampere-turns of the auxiliary cross winding oppose those of the rotor winding; hence the field circuit composed of these two

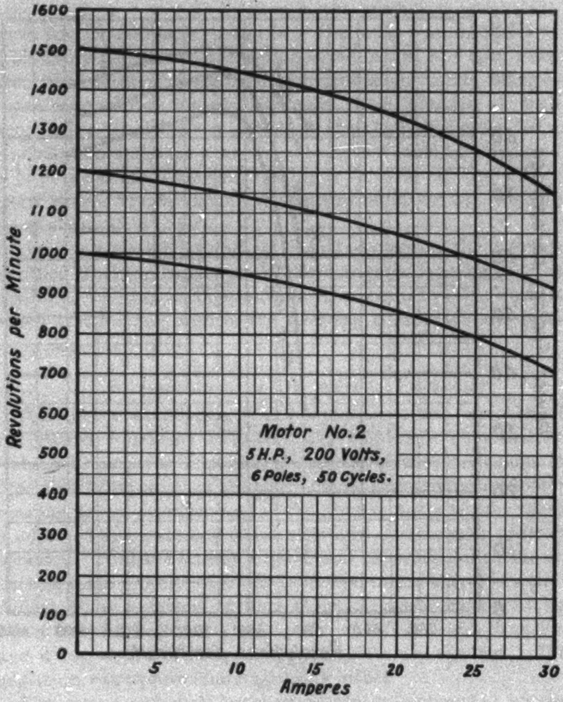


FIG. 27.

in series, has a comparatively low inductance. The correctness of the phase of the field flux depends upon the reactance of the field circuit being largely in excess of its resistance. At very low speeds, this will no longer be the case and the torque will begin to fall off.

The speeds between 600 and 1000 rev. per min. were obtained by field regulation while those above 1000 rev. per min. were obtained by using armature voltage control in addition. A constant compensation was used for all speeds except that of 600 rev. per min. where it was experimentally inconvenient to employ compensation. This was adjusted so as to give somewhat less than the maximum power-factor as it was found that at high speeds the compensating voltage applied to the exciting brushes produced quite a noticeable effect on the commutation under the armature or load brushes. Hence, only an amount of compensation sufficient to give the results of Fig. 28 was employed. The

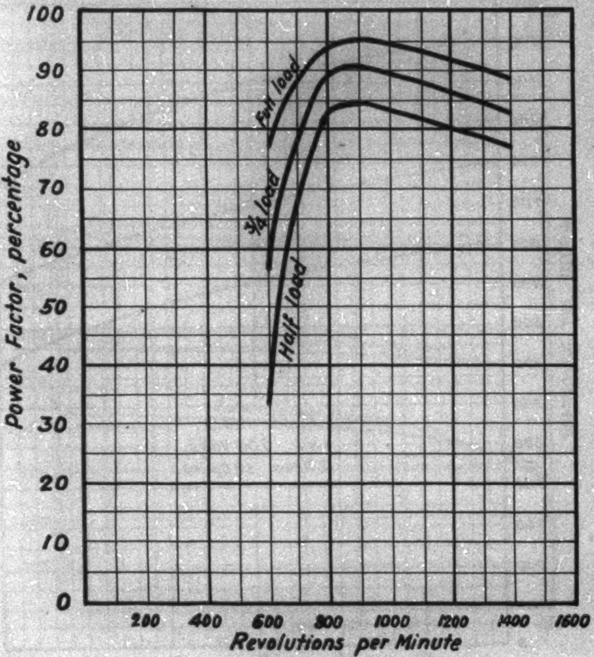


FIG. 28.

power-factor below synchronism could undoubtedly be brought up to that at other speeds by suitable compensating arrangements.

The efficiency of the motor has not yet reached a commercial figure, as it did not much exceed 70 per cent. Careful analyses of the losses were made and the low efficiency was found to be largely due to heavy $I^2 R$ losses in the brushes, a rather high brush friction and heavy iron loss This latter feature, however, is probably peculiar to the motor tested, which had open rotor slots, the winding being secured by numerous bands. Single-phase commutator motors, especially those intended for high frequencies, are never remarkable for their high efficiencies, but a recalculation indicates that the motor tested could be redesigned to have a full-load efficiency not below 78 to 80 per cent at any speed above synchronism, the maximum efficiency probably being about 83 per cent.

These tests, taken at various times and places in the intervals of other work, are sufficient, I believe, to show something of the possibilities of the machine. Some experiments by other workers which still further confirm the foregoing conclusions are, however, described below.

EXPERIMENTS OF DR. ALFRED FRAENCKEL

The author would like to call attention to the pamphlet of Dr. Alfred Fraenckel entitled "Der einphasige kompensierte Nebenschlussmotor" published in 1908, which contains a theoretical discussion of the compensated shunt induction motor running at synchronism and of the same motor when the speed is adjusted by means of a coil at right angles to the main primary winding. It also contains a number of experimental curves on both of these motors, of which I have taken the liberty of reproducing those relating to the adjustable-speed motor. This was a machine built for 8 horse-power at 200 volts and 50 cycles, and it ran at a synchronous speed of 1500 rev. per min. The armature was approximately 10 x 6¼ inches.

The motor ran sparklessly at all speeds represented by the curves in Fig. 29 to 32, except the very highest (1900 rev. per min. with no load) when there was considerable sparking at full load and overloads.

It will be seen from Figs. 30, 31, and 32 that the power-factor was very near to unity at all speeds, while the full-load efficiency varied between about 70 and 76 per cent.

For a 50-cycle motor this must be considered a very good performance. It will be seen that speed adjustment was obtained between about 1200 rev. per min. and 1900 rev. per min. or from

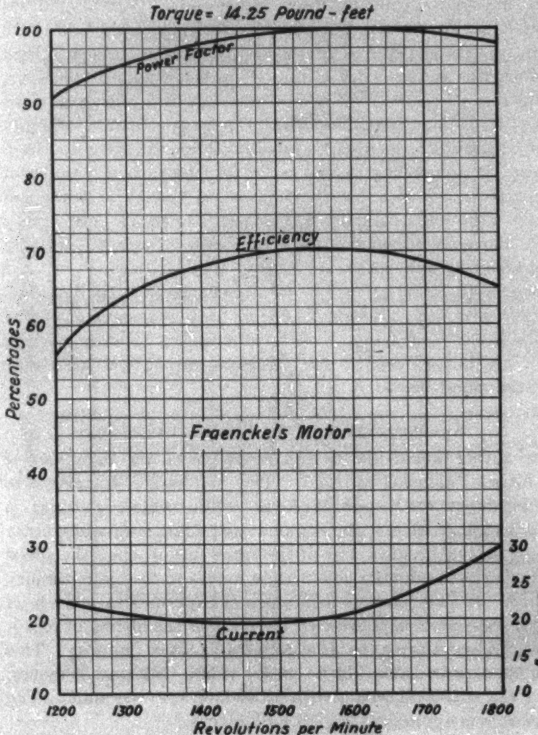


FIG. 29.

about 20 per cent below synchronism to 25 per cent above, a total range of 1.58 to 1.0. The percentage of reduction below synchronism agrees very closely with the writer's motor No. 3, while the latter, by the use of both field and armature control, could be brought up to twice the synchronous speed before the sparking became prohibitive.

It may be confidently stated, therefore, that a speed range of at least 2½ to 1 is possible on 25 cycles, while a speed range of 3 to 1 could certainly be attained with very little difficulty. If the frequency be increased, raising the speed of the motor in the same proportion and keeping the rotor voltage constant, the

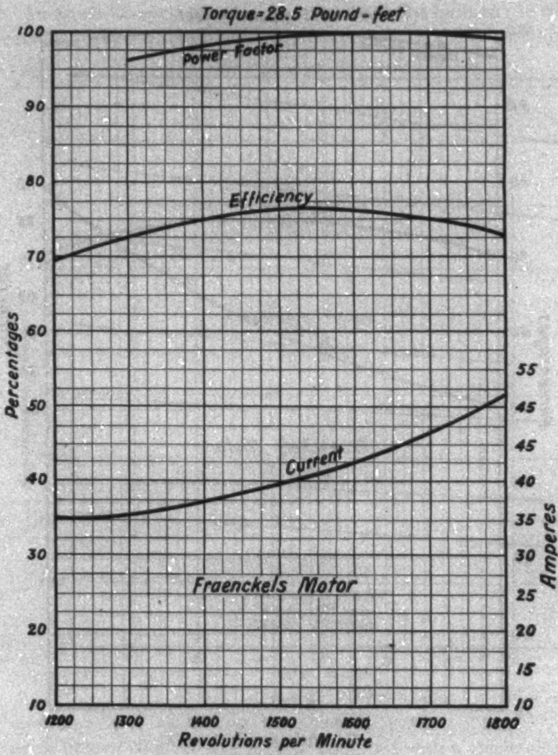


FIG. 30.

sparking voltage will be the same as before. In other words, if the 25-cycle motor be run at 60 cycles, keeping it at the same terminal voltage, the flux will decrease in inverse proportion

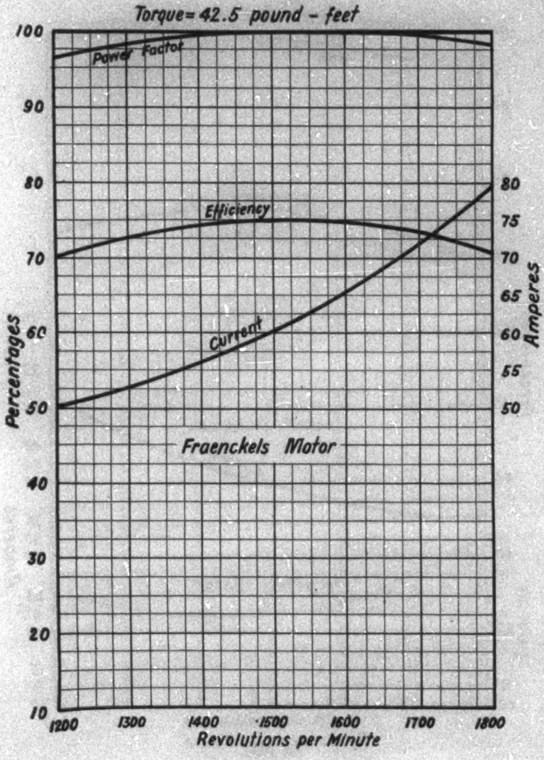


FIG. 31.

to the frequency and the speed will rise in direct proportion thereto. The power developed by the motor, of course, remains the same at all frequencies. Assuming that the commutator gives no trouble from vibration, etc.. at the higher speed, the commutation will be just the same as before, for the flux goes down in direct proportion to the increase in frequency. Hence the problem of building high-frequency motors reduces to that of building high-speed commutators.

An 8-pole 60-cycle machine could probably be built to run successfully between about 700 and 1600 rev. per min., and probably up to 1900 or 2000 rev. per min. if equipped with a mechanically good commutator. Such a machine would naturally be rather expensive but not more so than the compensated single-phase induction motor running near synchronism, as built by one American and several European firms. The efficiency would also be rather low, having about the same value as in the above-mentioned motor.

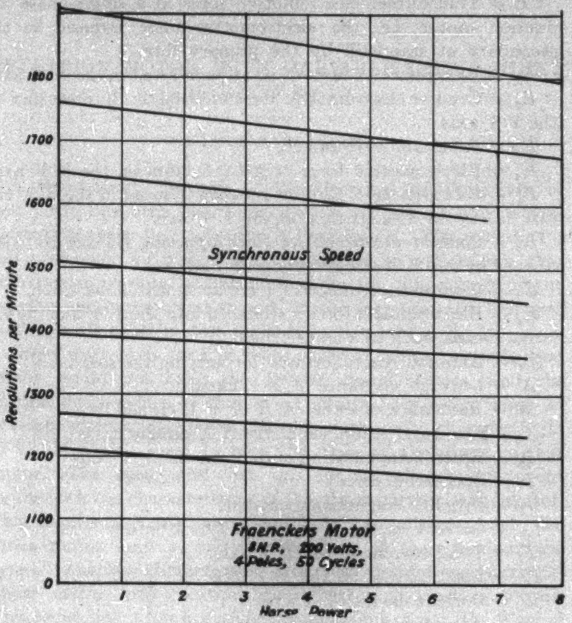


FIG. 32.

LIST OF SYMBOLS

E_0' = Compensating electromotive force.

E' = Total electromotive force induced by the field flux in the X X circuit (motor of Fig. 4).

E'' = Electromotive force induced by the field flux in that part of the X X circuit on the armature (motor of Fig. 4).

E = Transformer electromotive force in a single-phase induction motor; *i.e.*, the electromotive force induced in the secondary at standstill by the primary flux.

E_1 = Electromotive force of rotation induced in the X X axis.

E_2 = Counter electromotive force induced by the cross flux on the Y Y axis.

E_3 = Resultant of E and E_2.

E_4 = Electromotive force of self induction on the Y Y axis.

E_5 = Electromotive force of rotation induced in the X X circuit due to the leakage flux on the Y Y axis.

E_6 = Counter electromotive force opposing E_4 due to extra current in the X X circuit produced by E_5.

E_7 = Counter electromotive force at synchronous speed.

E_8 = Electromotive force introduced into the Y Y axis by external means, such as a transformer.

X_1 = External reactance used for varying the speed.

X = Leakage reactance of Y Y circuit.

R = Resistance of either X X or Y Y circuit.

$X_0 + X$ = Total reactance of the X X circuit.

I_3 = Extra compensating current on the Y Y axis.

I_s = Standstill current.

I_0 = Primary magnetizing current.

I_{1s} = Current on the Y Y axis at synchronism.

I_1 = Total current in the Y Y axis.

I_1' = Load current on the Y Y axis.

I_2 = Current on the X X axis.

k = Actual speed ÷ synchronous speed.

k_0 = Free running speed ÷ synchronous speed

$m = E_8 + E_7$.

σ = Dispersion coefficient.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

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REPULSION MOTOR WITH VARIABLE-SPEED, SHUNT CHARACTERISTICS

BY E. F. W. ALEXANDERSON

A characteristic feature of the electrical developments of late years has been the extension of the use of alternating-current to every field where it is practicable. The reasons for this preference for alternating current are so well known that reference need only be made: first, to the advantages of the distribution system; and second, to the fact that the best and most reliable of all motors is the induction motor.

Direct current is used in those cases in which the induction motor would not have the desired characteristics, and the natural consequence is that great efforts have been made to develop alternating-current motors with such characteristics as would enable them to take the place of the direct-current motor. The need most felt was for an alternating-current motor with the characteristics of the direct-current series motor. This requirement has been filled by the repulsion motor, the series motor, and certain modifications of these fundamental types. Another characteristic that was desired was a single-phase motor with constant speed and high starting torque. This requirement has been filled by the Milch motor, the Wagner motor, and some other similar types, all of which are of the repulsion-motor type in starting and run at constant speed as single-phase induction motors.

Although the advantages of alternating current for industrial plants are generally recognized, it is often necessary to recommend the use of direct current because many of the machines that are to be driven require a motor with adjustable speed. The direct-current shunt motor is the only one on the market which fills this requirement. If it is not practicable to have the plant wired for direct current as well as alternating current; all the constant-speed work must be done with direct current, although induction motors would be preferable for this purpose. The investigations and tests described in this paper have been made in order that this need arising in the development of alternating current, may be met by providing a motor with the characteristics of the direct-current shunt machine.

Before entering into a detailed description of any specific form of motor, it may be of interest to present a theory of the alternating-current machine in such a way as to indicate the possibilities of developing a motor with required characteristics.

When an induction motor runs at synchronous speed, the armature winding is stationary in relation to the magnetic field, which is assumed to rotate at a uniform velocity. It is therefore apparent that the conductors do not cut any lines of force and no electromotive forces are induced.

In giving the theory of a motor with adjustable speed, the subject can be made clearer by departing from the theory of the rotating field. If the strength of a rotating field fluctuates so that the maximum strength always occurs when the poles are in a certain position and the minimum strength in another position, the field may be called elliptical instead of a plain rotating field; however, the elliptical shape of the field does not in itself convey any idea as to the reason why the motor should tend to run at any other speed than that of the rotating field.

In the following, the rotating field will be treated as if it were composed of two alternating-current fields at right angles to each other. If an armature with a cummutator of ordinary construction is placed in such a field and two sets of brushes are arranged on the commutator in quarter-phase relation to each other, the following will take place: When the armature is at a standstill, a voltage will be induced between the positive and negative brush of each set, due to the alternating character of the two fields. Field *A* in Fig. 1, will induce a voltage between brushes *B* and vice versa. If the armature rotates at any speed, field *A* will induce an electromotive force between brushes *A*, and this electromotive force will be in opposition to the electromotive force induced by field *B* due to the alternating character of the field. In an ordinary induction motor, the two fields *A* and *B* are of equal strength, and in this case, the electromotive force of rotation will be completely neutralized by the electromotive force of alternation when the motor has reached synchronous speed. The armature has a tendency to run at a speed at which the induced currents are a minimum. All motors of this kind have only one free running speed, which is that of synchronism. This is true with motors of the commutator type, as well as the squirrel-cage and collector type, provided that the brushes are short-circuited.

If the condition which determines the speed of an alternating-current motor should be formulated broadly, the following might be stated:

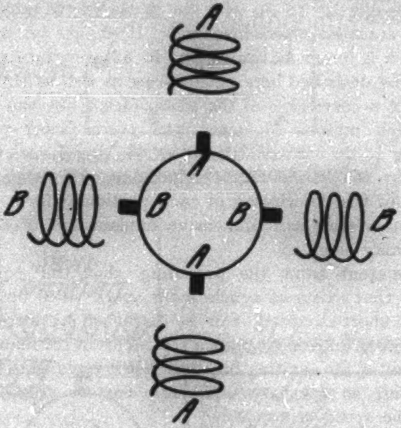

FIG. 1.

The motor tends to run at a speed at which the sum of all the electromotive forces in each of the armature circuits is zero. The electromotive forces to be considered are particularly the electromotive force of rotation and that of alternation; these two electromotive forces are always in opposition. A third electromotive force may be induced artificially by impressing a voltage on the circuit from outside.

The two sets of brushes in a repulsion motor of the compensated type may be classified as the main brushes and the exciting brushes; the main brushes carrying the energy current of the armature, the exciting brushes carrying the magnetizing current. If the main brushes as well as the exciting brushes are short-circuited, the motor will act like a single-phase induction motor. A practical modification of this motor has been developed by Milch, its principal feature being the power-factor regulation accomplished by impressing a suitable voltage on the exciting brushes. The impressed voltage is out of phase with the electromotive force of alternation and the electromotive force of rotation in the same circuit, so that it has nothing directly to do with the speed of the motor, which remains a constant-speed machine. It should be mentioned here that it is found advantageous in all commutator motors which will be described here, single-phase as well as three-phase, to introduce a correction of the power-factor like the one used in the Milch motor. However, the power-factor regulation has nothing to do with the theory of the speed variation, and reference to the power-factor regulation will, therefore, be omitted from the description of each particular form of motor in order that a more comprehensive explanation of the speed regulation may be given.

It is apparent from the preceding that the equilibrium of voltages that exists at synchronous speed when both sets of brushes are short-circuited, can be disturbed by introducing a voltage from the outside into either the circuit of the main brushes or the circuit of the exciting brushes; but it remains to be shown that in doing so another equilibrium can be established by changing the speed of rotation.

By a simple calculation, it can be shown that the relation between speed and field strength and the impressed voltages can be expressed as follows:

$$\text{Speed} = \text{Synchronous speed} \sqrt{\frac{E+e}{e}}$$

$$\frac{F_1}{F_2} = \sqrt{\frac{\text{speed}}{\text{synchronous speed}}}$$

where E is the voltage impressed on the stator winding reduced to number of turns in the armature, and e is the voltage impressed on the armature. F_1 and F_2 are the two components of the field in the axis of the exciting brushes and the axis of the main brushes, respectively. The voltage which is impressed on the armature may be either positive or negative, and consequently the speed can be regulated below synchronous speed as well as above synchronous speed. The method for speed

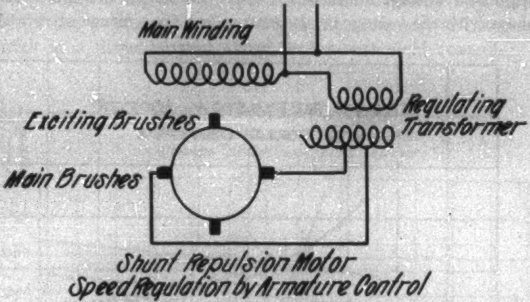
Main Winding
Regulating Transformer
Exciting Brushes
Main Brushes
Shunt Repulsion Motor
Speed Regulation by Armature Control

FIG. 2

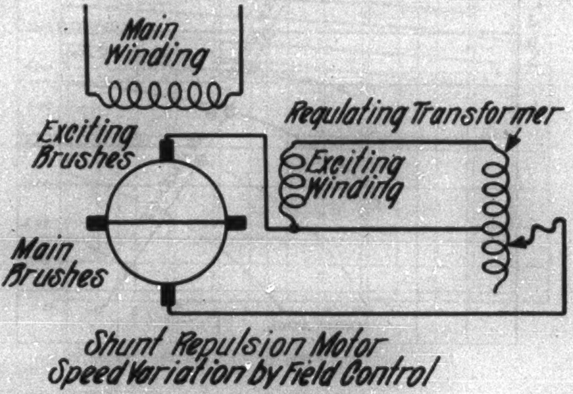
Main Winding
Regulating Transformer
Exciting Brushes
Exciting Winding
Main Brushes
Shunt Repulsion Motor
Speed Variation by Field Control

FIG. 2A.

variation described can be classified as armature control, because the functions correspond to those of a direct-current shunt motor when the speed is varied by raising and lowering the line voltage.

The second method for varying the speed of the repulsion motor follows logically. As shown in Fig. 2, the short-circuit is maintaned on the main brushes, while an external voltage is impressed upon the exciting brushes. In order to make the impressed voltage effective for speed variation, it should be in phase with the voltage of alternation and the voltage of rotation of the same circuit. These voltages in the exciting circuit are out of phase with the line voltage and, consequently, the line voltage cannot be used for varying the speed; however, if the motor has an exciting winding, like a plain repulsion motor, in addition to the exciting brushes, a voltage is found on the terminals of the exciting winding which has a suitable phase to be used for speed variation by field control.

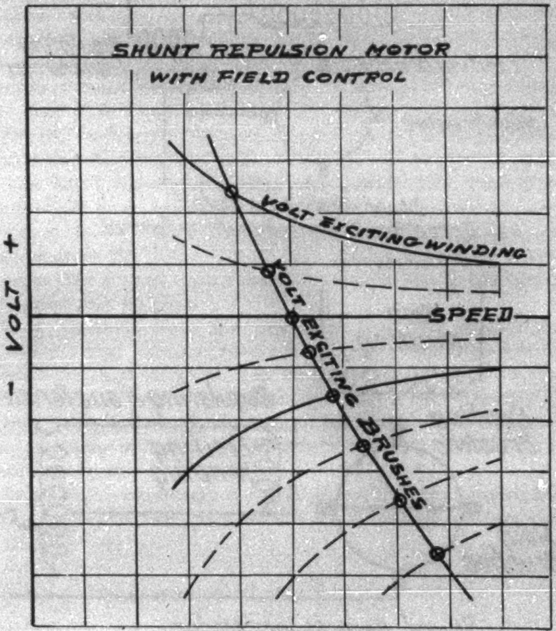

Fig. 3.

The equilibrium of voltages is reached by a combined change of field strength and speed, for the same reason as in the case of armature control; however, the functions of the two fields are different; the entire energy supply is introduced through the stationary winding and the speed variation is obtained by variation of the torque-producing field, in the same way as the speed varies in a direct-current shunt motor with field control.

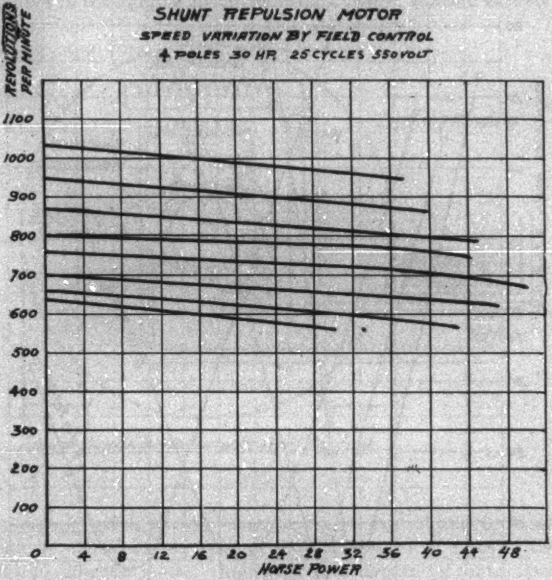

FIG. 4.

The relation of voltages which gives the equilibrium in the two brush circuits is not quite as simple to figure out as in the case of armature control; because the voltage impressed upon the brushes for the sake of speed variation is not derived from a constant source of potential, but from a winding which delivers a voltage that is in itself a function of the speed. However, the relations become comparatively simple by returning to the theory of the plain repulsion motor and plotting curves for the voltage that would naturally occur at the exciting winding and the exciting brushes at different speeds. The voltage of the exciting winding is always positive, but varies inversely with the speed; while the voltage of the exciting brushes is positive below synchronous speed and negative above synchronous speed. Fig. 3 shows curves of these voltages plotted on the same sheet. Only one curve is shown for the voltage of the exciting brushes, while the voltage of the exciting winding is plotted on the posi-

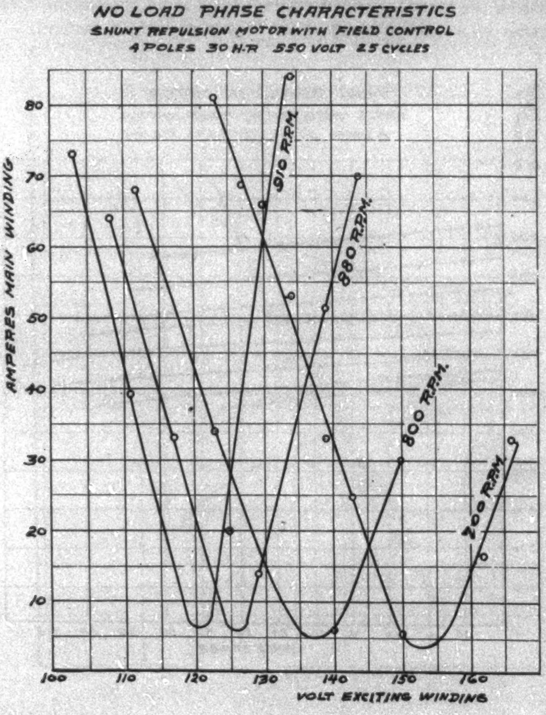

FIG. 5.

tive as well as on the negative side. The dotted curves indicate different voltages that may be derived from the exciting winding by the use of a step-up and a step-down transformer. The points marked in the intersections between the curves indicate equilibrium of voltages that may be obtained at different speeds by impressing on the exciting brushes the different voltages derived from the exciting winding.

The tests, which have been made on a 30-h.p., 25-cycle motor and a 3-h.p., 60-cycle machine in order to demonstrate the possibilities of the alternating-current shunt motor, confirm entirely the theory given above. The curves in Figs. 4 and 5, which may be considered as typical, show the results of tests of the 30-h.p., 25-cycle motor. Fig. 2 shows a diagram of connections giving the principal features of armature control as well as of field control. The connections used for controlling the power-factor have purposely been omitted from these diagrams because they are apt to make confusion and have nothing to do with the point that is to be illustrated. A practical control diagram for the motor with field control is shown in Fig. 6.

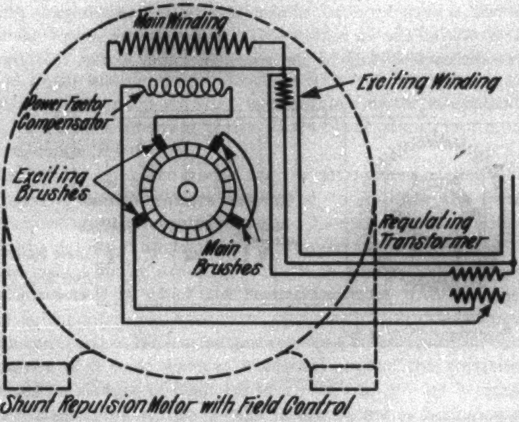
Main Winding
Exciting Winding
Power Factor Compensator
Exciting Brushes
Main Brushes
Regulating Transformer
Shunt Repulsion Motor with Field Control

FIG. 6.

The power-factor of any commutator motor with shunt characteristics, single-phase as well as three-phase, canbe regulated in a manner similar to that of a synchronous motor. The functions of the power-factor regulation are the same as in the synchronous motor and can be best understood if they are described from the same point of view. The power-factor characteristics of a synchronous motor are usually illustrated by a curve showing the leading and the lagging current taken by the motor at no load with different field excitations. This curve is illustrated in most treatises on the synchronous motor and is recognized by a characteristic V shape. Fig. 5 shows the corresponding V-shaped phase characteristic for the shunt repulsion motor.

While a synchronous motor has only one no-load phase characteristic, the variable-speed shunt repulsion motor has one curve for each setting of the speed; in other words, the power-factor can be varied at will at each speed by adjusting the excitation. In the commutator motor, as well as the synchronous motor, the power-factor regulation consists in superimposing a wattless current upon the current that would otherwise be taken by the motor. It is known from the theory of the synchronous motor, that the power-factor can be maintained practically at unity between no load and full load with one fixed excitation, provided the excitation has been adjusted for the average load. The same is the case with the commutator motor. The regulation of the field for the purpose of adjusting the power-factor is accomplished in the commutator motor by a transformer or a coil in the stator winding, connected so as to introduce a fraction of the line potential in the exciting circuit. By varying the voltage introduced in this way, the amount

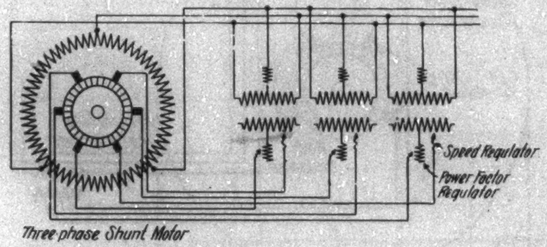

FIG. 7.

of wattless current can be regulated, as shown in Fig. 5. The complete diagram for the shunt repulsion motor with field control, illustrated in Fig. 6, shows the feature of power-factor regulation introduced by a coil of the stationary winding.

In connection with this subject, it will undoubtedly be of interest to refer to the possibilities of the three-phase motor with shunt characteristics. The possibility of such a motor was demonstrated theoretically by Georges about ten years ago, and tests of such a motor were made several years ago by Eichberg and Alexander. The speed variation of the Georges three-phase shunt motor is obtained by maintaining a constant field and adding or subtracting voltage to the armature circuit. The power-factor of the three-phase shunt motor can be regulated in the manner described above for the single-phase motor, and the comparison with the synchronous motor is applicable. Fig. 7 shows a diagram of the three-phase shunt motor with power-factor regulation.

In the theory given above for the alternating-current shunt motors, it has only been attempted to indicate the general principles, and the scope of this paper does not permit of entering into the details of application. However, it may be stated that speed variation by armature control is particularly applicable to those cases in which the torque increases with the speed, and field control to those cases in which the torque decreases with the speed. With armature control a speed variation can be obtained of 3 to 1; whereas with field control the variation is limited to a range of from 1.5 to 1. It will not be attempted to compare the merits of the three-phase and single-phase shunt motor; however; it may be stated as the impression of the author that the single-phase shunt motor will be preferred on account of the greater simplicity of control.

DISCUSSION ON " A SKETCH OF THE THEORY OF THE ADJUSTABLE-SPEED, SINGLE-PHASE, SHUNT INDUCTION MOTOR," AND " REPULSION MOTOR WITH VARIABLE-SPEED, SHUNT CHARACTERISTICS." FRONTENAC, N. Y., JUNE 28, 1909.

V. Karapetoff: I would like to ask Mr. Creedy the reason for calling this motor an induction motor? It seems to me that it would cause some confusion in our nomenclature. An induction motor, according to present nomenclature, is a motor without a commutator. I think that the title of the paper should be " A Sketch of the Theory of the Adjustable-Speed, Single-Phase, Shunt, Commutator Motor."

E. F. Alexanderson: The paper by Mr. Creedy on the shunt induction motor treats of the same subject as my paper on the shunt repulsion motor and the difference in the subject matter appears to be only the name. Mr. Creedy's paper therefore affords an excellent opportunity for comparing the viewpoints of similar investigations carried on independently.

In regard to the technical definition of certain terms used in both papers, it may be pointed out that the terms " adjustable-speed motor " and " shunt motor " are used to signify a motor having the characteristics of a direct-current shunt motor with field control. It is possible to obtain variation in speed by methods which do not give shunt characteristics. For instance, the speed of the ordinary induction motor can be varied by introducing resistance in the secondary winding. In certain cases the introduction of reactance will give the same results. A speed variation obtained in this way is similar to the speed variation of a series motor. Motors of various makes using this type of speed variation have been in the market for some time in Europe as well as in America.

The speed variation by introduction of resistance in the secondary has been used to some extent in the American built Milch motor in cases where speed variation by this method is applicable. The motor which Mr. Creedy refers to as being the only motor of a similar type built in this country, is apparently the motor which I dealt with particularly in investigating the possibilities of an adjustable-speed shunt motor. This motor has been on the market for several years and is known as the Milch motor. It is classified as a repulsion induction motor. The diagram in Fig. 21 of Mr. Creedy's paper illustrates this type.

In my paper it has not been attempted to describe early types of motor or to mention names of inventors, because so many have been working along the same lines that it is difficult to give credit to some without doing injustice to others. My investigation has been based on the assumption that the system for compensating the power-factor developed by Milch is essential for the success of any motors of this class. This conclusion Mr. Creedy has also reached and a direct statement to that effect is made in his paper. The object of my paper is simply to give the results of an investigation as to what practical additions can be made to the constant-speed motor developed by Milch in order to introduce the adjustable-speed feature.

For this purpose not only the theoretical possibilities but also the established practice in manufacturing had to be considered. The aim has been to develop such a method of control that the constant-speed, repulsion, induction motor of a well-known make could be used for adjustable-speed work with the least amount of modification. In the first attempts it appeared as if speed variation by field control, illustrated in Fig. 6 in my paper and in Fig. 4 of Mr. Creedy's paper, would be the most applicable.

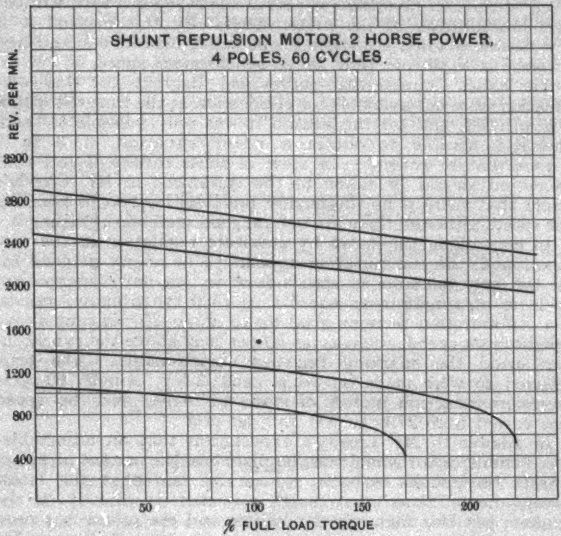

FIG. 1.

The experimental data obtained from a test of the 30-h.p., 25-cycle motor built for experimental purposes, were worked out with reference to field control. The results are shown in Figs. 4 and 5. Subsequently, a 3-h.p., 60-cycle motor was built, adhering as closely as possible to the manufacturing methods developed for the constant-speed motor. In designing this motor it appeared that a motor of the original type could always be furnished by adjustable-speed field control, provided the motor was of the reversing type; in other words, provided it had a section of the field winding placed in quarter-phase relation to the main part of the winding. The method of speed variation with armature control was also reconsidered, and it was found that a suitable arrangement of the controlling circuit made it possible to apply a practical system of speed variation to the original type of motor which is being built at present for constant speed. The speed variation can be applied to the non-reversible as well as the reversible type without any modification of the motor itself. By this method it is practicable to lower the speed to one-half synchronous speed, and increase it to 50 per cent above synchronous speed.

The exact characteristic curves and diagrams for this combination were not available for publication at the time the paper was printed, and for this reason it was only possible to state that it is feasible to obtain a speed variation of 3 to 1 with armature control. In view of these results, I feel that exception should be taken to the statement in Mr. Creedy's paper that there is no thoroughly practical method of lowering the speed, although there are several good methods of raising it

In controlling the speed by armature regulation in the way mentioned, the commutation appears to be nearly as good for all the sub-synchronous speeds down to one-half synchronism as it is at synchronous speed. At over-synchronous speeds, the commutation remains good up to about 30 per cent above synchronous speed, whereas at 50 per cent above the synchronous speed the sparking becomes objectionable. The tests referred to were made on 3-h.p. and 2-h.p., 4-pole, 60-cycle repulsion induction motors of standard make, and the speed was varied from 2700 to 900 rev. per min.

In answer to Mr. Creedy's expectation that an adjustable-speed shunt motor would soon be placed on the market in either Europe or America or both, it can be said that the latest developments show that such a motor is already on the market; but this fact was not known and the motor has been considered as a constant-speed motor, due to the lack of a suitable controlling device. Owners of such motors may be interested to know that it will be possible to add such a controlling device for adjustable speed to their equipments as soon as such a device has been developed.

My paper was not intended to cover all the possible connections. The investigation I made was for certain practical purposes, in conjunction with established practice of manufacture, and therefore it might not be of sufficient interest at the present time to go into detail in answering questions relating to the different connections that may be suggested.

F. Creedy (by letter): I am interested in Mr. Alexanderson's paper, as it contains the results of an independent investigation of a subject on which I also have done a good deal of work. At the stage at which this motor has at present arrived, one may say that the principal problem before us is to keep the efficiency up and the cost down. It will probably be found that any constant-speed compensated motor of the type shown in Fig. 21 of my paper can be modified to form an adjustable-speed motor. If the speed range is high say, 3 to 1, a somewhat larger commutator will be required, but the same frame can be used and rated so as to give the same horsepower at synchronous speed.

I would like some information in regard to the diagram of connections, Fig. 6. Redrawing this in a manner corresponding to the other diagrams it would appear as in Fig. A. I am inclined to think that such a motor, while it may be arranged for self-starting without change of connections, will be somewhat intermediate in its characteristics between shunt and series motors and will have a more drooping speed characteristic than the plain motor without a quadrature coil in the primary circuit. It reminds me of a motor proposed some years ago in one of the early patents (see Fig. B) in which the coil usually wound in quadrature is wound at a certain angle with the primary coil, and the brushes are then moved so as to get the best ratio between the compensating and the speed-increasing electromotive forces. This motor has, I believe, similar characteristics, although the connection is quite different. I should be glad to know whether Mr. Alexanderson's experience bears out these views. When considering these single-phase, adjustable-speed motors the Görges polyphase adjustable-speed motor naturally comes up for consideration also. Like Mr. Alexanderson I have done some figuring on such motors, and, like him, I have come to the conclusion that the much greater simplicity and flexibility of the control will always give the advantage to the single-phase motor in spite of its somewhat greater weight per horse power.

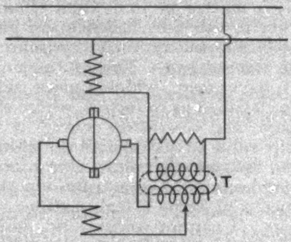

Fig. A

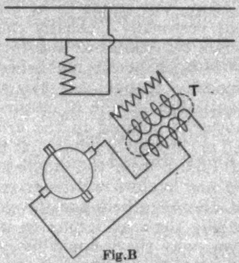

Fig. B

I do not think that Mr. Alexanderson's remarks on my paper call for any very extended reply, as I find myself in complete agreement with nearly everything he says. I am much interested in the tests shown in Fig. 1 of his discussion, which show a wider speed range than any which have hitherto been published. I presume, however, that a commercial motor would be built with six poles having a range of from 600 to 1800 rev. per min. Since writing my paper, further investigation had begun to convince me also that I had somewhat underestimated the possibilities of speed reduction by armature control, so I am quite willing to modify the statement to which Mr. Alexanderson takes exception.

I think that in view of the results of these two papers we may fairly say that we are at least in possession of that complement to the induction motor which has been sought for so long; namely, a practical adjustable-speed, alternating-current motor. Its manufacture will probably be taken up in the near future.

With reference to Professor Karapetoff's remarks on nomenclature; this seems to be largely a matter of individual choice, but personally I usually endeavor to use the classification proposed by Atkinson* and further developed by V. A. Fynn in a little book he has published on the subject. This is the only logically thought-out system I have seen, which avoids self-contradiction. In it, motors are classified as *inductive*, where the power is induced in the armature, and *conductive* where it is led in through brushes. It is impossible to distinguish the motor of Fig. 1 from the single-phase, squirrel-cage, induction motor on any ground whatever except mechanical construction, and as all the others are developments of this, I feel justified in calling them all induction motors. I cannot understand, however, why they should be called repulsion motors, as according to my idea a repulsion motor is essentially a machine with series characteristics.

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* Proc. Inst. Civil Eng., London, 1898.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

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THE HEATING OF INDUCTION MOTORS

BY A. MILLER GRAY

The object of this paper is to show the limitations imposed on the designer of induction motors by the heating of the machine, and also to show how this heating may be predetermined.

The highest temperature at which an electrical machine should ever be operated, is that at which the insulation begins to deteriorate owing to the action of heat. With the present practice in insulating, the temperature of the stator coils of an induction motor should not exceed 85° cent. for any length of time. The same limitation holds for the rotor coils of a wound rotor machine. The temperature of the rotor of a squirrel-cage motor is only limited by the fact that a hot rotor causes a hot stator, because the hot air from the rotor has usually to pass through the stator coils before it gets out of the machine.

Heating conditions at starting. The squirrel-cage induction motor, with full applied voltage at the terminals, gives a starting torque of about 1.8 times full-load torque, with about 6 times full-load current, or, for full-load torque, the current in the motor is 4.5 times full-load current.

The operation of such a machine can best be shown by the circle diagram Fig. 1.

a b—represents the loss in the rotor end connectors, with the rotor in the locked position.

b c—that in the rotor bars.

c d—the rotor stray loss, which cannot be calculated.

d e—the stator stray loss, which cannot be calculated.

e f—the stator I^2R loss.

f g—the windage, friction, and core loss, which are assumed constant.

At starting, the losses in a squirrel-cage motor are very large, while the speed, on which the power of the motor to get rid of heat depends to a great extent, is low, therefore the heat generated in the various parts of the machine at starting, must be absorbed by these parts.

To determine the temperature rise of the rotor bars at starting. The resistance of copper at the usual working temperature of a motor is 1 ohm per circular mil per inch, therefore the loss in the rotor bars = I^2R watts.

$$= \frac{I^2 \lambda n}{\textcircled{M}} \text{ watts.}$$

Where I = the effective rotor current in each bar.
λ = the length of the rotor bar in inches.
n = the number of bars.
$\textcircled{M}$ = the area of each bar in circular mils.

The heat absorbed by the rotor bars =
$n \times \lambda \times \square'' \times .32 \times .092 \times \theta$ calories per sec.

Where $\square''$ = the area of each bar in sq. in.
0.32 = the weight of 1 cu. inch of copper.
0.092 = the specific heat of copper.
θ = the temperature rise per sec. in degrees cent.

$$\frac{I^2 \lambda n}{\textcircled{M}} \text{ watts} = \frac{I^2 \lambda n}{\square'' \times 1.27 \times 10^6} \times \frac{1}{746} \times \frac{550}{1} \times \frac{1}{774} \times \frac{5}{9}$$

calories per sec.

$$= \frac{I^2 \lambda n}{\square'' \times 1.27 \times 10^6} \times 0.00053 \text{ calories per sec.}$$

$$= n \lambda \square'' \times 0.32 \times 0.092 \times \theta$$

therefore θ = temp. rise per sec. in deg. cent. $= 1.4 \times 10^{-8} \left(\frac{I}{\square''} \right)^2$

$$= 2.28 \times 10^4 \left(\frac{I}{\textcircled{M}} \right)^2 \qquad (1)$$

The value $\frac{\textcircled{M}}{I}$ is seldom less than 400 in the rotor bar at full load, and therefore for full-load torque at starting the $\frac{\textcircled{M}}{I} =$

the circular mils per ampere $=\frac{400}{4.5}$ approx. $= 89$; and the temperature rise per second from equation 1 = 2.9 degrees cent.

To determine the size of the rotor end connectors. Let P_c be the loss in each ring in watts at starting, required to give the necessary starting torque.

$$\begin{aligned} P_c \text{ watts} &= P_c \times 0.00053 \text{ calories per sec.} \\ &= \omega \times S \times \theta \end{aligned}$$

Where ω = the weight of each ring in lb.
S = the specific heat of the rings assumed = 0.092.

therefore,

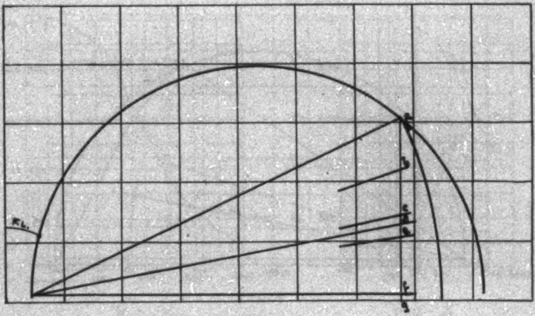


FIG. 1

the temperature rise per sec. per watt per lb.

$$= \frac{0.00053}{0.092} = \frac{1}{173} \text{ degrees cent.} \qquad (2)$$

or for 1 synchronous h.p. per lb. the temp. rise = 4.3° cent. per sec. The proper weight of ring to be used in any particular case depends on the starting torque required, and the time needed to bring the motor up to speed. For motors up to about 50 h.p., where the starting duty is not severe, 1.5 synchronous h.p. per lb. will give satisfactory results.

To determine the temperature rise of the stator windings at starting This may be found in a similar way to that used for the determination of the temperature rise of the rotor copper; namely:

$$\theta = \text{temp. rise per sec. in degrees cent.} = 2.28\times\left(\frac{I}{\textcircled{M}}\right)^2 \times 10^4$$

This temperature rise cannot be measured by thermometer, because the rate of increase of temperature is so rapid that the heat does not get through the insulation. In making static torque tests on induction motors, the stator coils may often be smoking and yet the coils not feel exceptionally warm to touch.

Test results. The following starting tests are of interest in connection with the previous discussion. A squirrel-cage induction motor was supplied with rings of extra high resistance

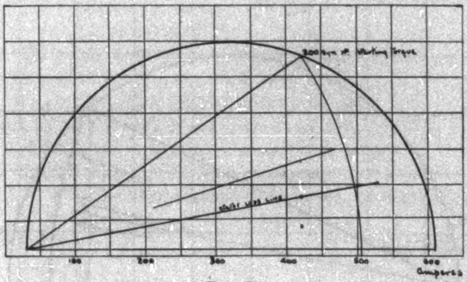


FIG. 2.

and was connected up for experiment to a rotating mass having a large moment of inertia and a small friction loss. Such a rotating mass is found in the rotating field of a turbine alternator.

The operation of the machine in question is shown by the circle diagram Fig. 2.

The moment of inertia of the rotating mass = 36,000 lb.-ft.^{2}

The tests were made on half voltage, under which conditions the

$\frac{\textcircled{M}}{I}$ stator = 249

$\frac{\textcircled{M}}{I}$ rotor = 164

Weight of each ring = 23 lb.

P_c = watts lost in each ring = 13750 watts = 18.5 synchronous h.p.

H.p. per lb. of ring = 0.8

The calculated temperature rises per second from equations 1 and 2 are:

stator coils—0.37 °cent.

rotor bars—0.85 °cent.

rotor end connectors—3.4 °cent.

The speed-time and current-time curves of the machine are shown in Fig. 3. About 60 seconds after starting, smoke began to come from the stator windings, and the stator continued to smoke until the speed rose to 50 per cent of full-load speed, at which point the stator current had fallen to 83 per cent of the starting current, and the ventilation was more than able to take care of all the heat generated.

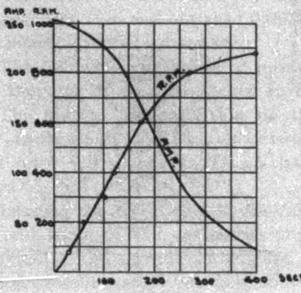


FIG - 3

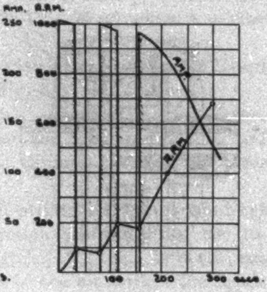


FIG - 4

At 253 amperes starting current, the circular mils per ampere is 249 and the calculated temperature rise 22° cent. in 60 seconds, which is not sufficient to cause the machine to heat up as it did. To test this point a direct current of 300 amperes was sent through all three phases of the stator; the rotor was stationary. Under these conditions the temperature rose from 16° cent. to 103° cent. by thermometer in six minutes, at which temperature smoke began to appear. The cause of the excessive heating when the motor was started up must therefore have been the high temperature of the rotor end connectors. The construction of this machine is similar to that shown in Fig. 5. The rotor end connectors *H* are close to the stator windings *E* so that, if the former are very hot, the latter will be scorched on the outside. In the actual test the rings began to oxidize in about a minute after starting, and they were highly discolored before the motor was up to speed.

The total rotor loss at starting = 37,000 watts.
= 50 syn. h.p.
The weight of two end connectors = 46 lb.
of rotor bars = 66 lb.
of rotor laminations = 200 lb.
Total rotor 312 lb.

If the heat generated in the rotor bars and end connectors had time to diffuse all through the rotor, the rotor temperature rise would be from equation (2)

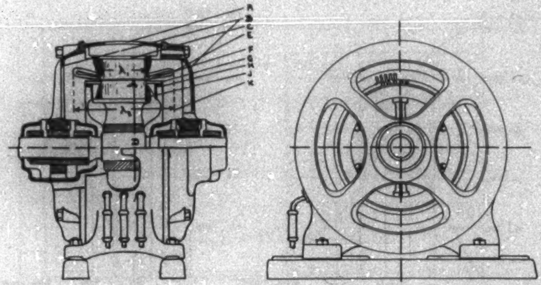


Fig-5

$$\frac{50}{312} \times 4.3 = 0.61^\circ \text{ cent. per sec.}$$

An attempt to approximate this condition was made by bringing the machine up to speed in steps as shown in Fig. 4. In this case the rings remained untarnished and the temperature rise on the windings was only 51° cent. by thermometer. The machine showed no signs of high temperatures.

Heating of induction motors under running conditions. Before discussing any particular type of construction or system of ventilation, attention must be drawn to the fact that in an induction-motor stator, built up of laminations which are insulated from each other by paper or by varnish, the thermal conductivity of the core is not the same in all directions; for example,* in the case of a core built with alternate layers of iron 0.020 in. thick and of paper 0.002 in. thick, the conductivity was as follows:

Along the laminations—0.1365 gram calories per cm. per sec. per degree cent.

Across the laminations—0.0013 to 0.0025 gram calories per cm. per sec. per degree cent.

The latter quantity varied with the structure of the paper and the kind of scale on the iron.

It was also found, by blowing air across the radiating surface of the core, that the watts per sq. cm. radiating surface per degree cent. rise was equal to $0.0038\ (1+0.25\ v.)$ where $v =$ the air velocity in metres per sec.

The following discussion of induction motor heating is based on the type of machine shown in Fig. 5.

The system of ventilation of this machine is as follows: air is drawn in at K, passes between the rotor end head J and the rotor end connector H and then through between the rotor bars G.

Leaving the rotor, the moving air strikes the stator windings F and some of the air passes through the windings; the remainder of the air moves along the coils to E, then, as it still has a considerable radial velocity, some of the air strikes the inside of the housing at B, and is deflected back over the outer surface of the stator coils and then over the laminations C, before it leaves the machine at A.

An important feature about the construction of this machine is that the moving air is not passed out of the machine after cooling the stator coils, but passes over the back of the stator laminations with a fairly high velocity, in this way getting the effect, which the experiments on conduction just mentioned would indicate as desirable to obtain.

Table I gives a number of heat runs on a motor of this type and of the following dimensions:—

$D =$ dia. of rotor $= 33$ in.
$\lambda_1 =$ length of core $= 4.5$ in.
$\lambda_2 =$ length over coils $= 15.125$ in.

---

* *London Electrician*, March 7, 1907.

TABLE I.

Test No.	Stator loss in kw.			Stator temp. rise in °cent.				$\frac{I^2R - \text{core loss}}{\text{core loss}}$	$\frac{\text{core loss} - I^2R}{I^2R}$	$\frac{\text{temp. rise copper}}{I^2R}$	$\frac{\text{temp. rise iron}}{\text{core loss}}$
				Machine running		After shut down					
	I^2R 1	Core loss 2	Total 3	Copper 4	Iron 5	Copper 6	Iron 7	8	9	10	11
1	2.09	1.6	3.69	21	22	21½	22	0.307	−0.235	10.3	13.8
2	2.8	1.6	4.4	24½	23	27	26	0.75	−0.428	9.65	16
3	3.08	1.6	4.68	26	25	27.7	26.5	0.925	−0.48	9.0	16.6
4	2.9	3.7	6.6	26	29	30	31	−0.216	0.275	10.4	8.4
5	3.64	3.7	7.34	35½	35½	36½	36½	−0.016	0.0165	10	9.9
6	2.2	4.2	6.4	21	25½	22	26	−0.475	0.91	10	6.2
7	3.6	4.2	7.8	33	34½	34	35½	−0.143	0.166	9.5	8.4

$\sim$ = frequency = 60 cycles.
p = number of poles = 10.
synchronous speed in rev. per min. = 720
S = % slip at full load = 4% approx.

Column 1 gives the stator $I^2 R$ in kilowatts.

R is the resistance at the air temperature measured by direct current. The eddy-current loss is negligible, because the core is short. and the conductor in no case is more than 0.5 in. deep.

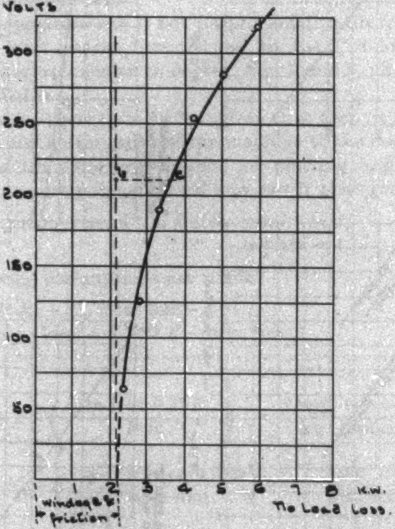


Fig. - 6
Induction Motor Core Loss Curve

Column 2 gives the stator core loss in kilowatts. This is taken directly from the saturation curve Fig. 6 in the following way:

The saturation curve in Fig. 6 is taken as low as possible and is then continued as shown by dotted part to the base line. The core loss at 220 volts then = $b\ c$ = 1.6 kw.; at 330 volts = 3.7 kw. and at 360 volts = 4.2 kw.

Columns 4 and 5 give the temperatures of the stator copper and iron while the machine is still running under load.

Columns 6 and 7 give the same temperatures after the machine has been shut down and the heat has come out, to use a shop phrase. The temperature always rises a little after shut-down because, under running conditions, the internal parts of the machine are hotter than the parts on which the thermometers are placed; while after shut-down, the temperature tends to become uniform throughout the stator.

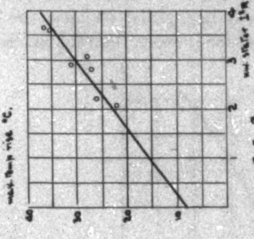


FIG-8

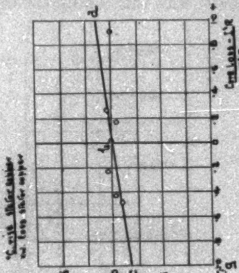


FIG-10

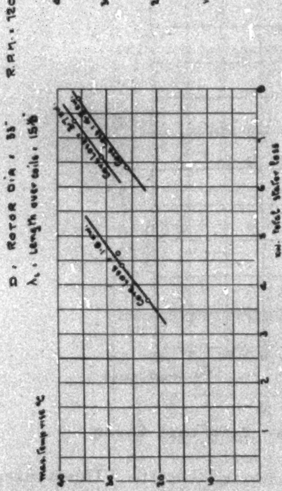


FIG-7

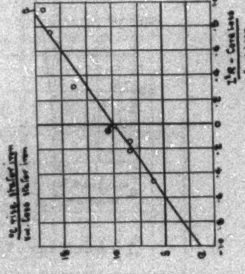


FIG-9

These temperatures are all measured by thermometer. In the case of the stator coils the thermometer bulb is pushed into the windings and is protected from the direct ventilation of the machine. In the case of the stator iron, the thermometer bulb is laid on the back of the laminations at a point where it is protected from air blowing through the vent ducts. The bulb is then covered with a pad of waste. This pad is in such a position and is of such a size that it will not interfere with the natural ventilation of the machine.

Two important points are to be seen from these tests:

1. Irrespective of the distribution of the stator loss between the copper and the iron, the final temperature of the copper, after shut-down, is approximately equal to the final temperature of the iron, in any one test.

2. The temperature rise is not proportional to the total stator loss. It is more nearly proportional to the $I^2 R$ loss of the stator. This is well shown in curves, Fig. 7 and 8, plotted from the tests of Table I.

The former of these two points shows that there is a transfer of heat from the hotter parts of the machine to the cooler parts, and suggests the following method of plotting heating data. The method is purely an empirical one, but it gives good results.

The temperature rise of the stator iron $= t_2$
" " " " " " copper $= t_1$

The following assumptions are made

$$t_1 = K_1 (I^2 R) + K_2 (\text{core loss} - I^2 R)$$
$$t_2 = K_3 (\text{core loss}) + K_4 (I^2 R - \text{core loss})$$

or

$$\frac{t_1}{I^2 R} = K_1 + K_2 \left(\frac{\text{core loss} - I^2 R}{I^2 R}\right) = \frac{\text{temp. rise copper}}{\text{kw. copper loss}}$$

$$\frac{t_2}{\text{core loss}} = K_3 + K_4 \left(\frac{I^2 R - \text{core loss}}{\text{core loss}}\right) = \frac{\text{temp. rise iron}}{\text{kw. iron loss}}$$

The curve in Fig. 9 gives

$$\frac{t_2}{\text{core loss}} \text{ plotted against } \frac{I^2 R - \text{core loss}}{\text{core loss}}$$

The curve in Fig. 10 gives

$$\frac{t_1}{I^2 R} \text{ plotted against } \frac{\text{core loss} - I^2 R}{I^2 R}$$

from the tests of Table I.

TABLE II.

Stator loss in kw.			$\frac{I^2R - \text{core loss}}{\text{core loss}}$	$\frac{\text{core loss} - I^2R}{I^2R}$	temp. rise copper I^2R from curve—10	temp. rise iron core loss from curve—9	Calculated temperature rise	
I^2R	Core loss	Total					Copper	Iron
1	6	7	−0.83	5.0	19° C.	3° C.	19	18
2	5	7	−0.6	1.5	12.7	5	25	25
3	4	7	−0.25	0.33	10.6	8	32	32
4	3	7	0.33	−0.25	9.6	13	38	39
5	2	7	1.5	−0.6	9.0	23	45	46
6	1	7	5.0	−0.83	8.6	53	52	53

TABLE III.

Test No.	Amp. stator	Kw. stator loss		° cent. temp. rise					$\frac{I^2R - \text{core loss}}{\text{core loss}}$	$\frac{\text{core loss} - I^2R}{I^2R}$	$\frac{\text{temp. rise copper}}{I^2R}$	$\frac{\text{temp. rise iron}}{\text{core loss}}$
				Stator		Rotor						
		I^2R	Core loss	Copper	Iron	Cond.	Ring	Iron (inside)				
1	180	2.9	4.1	28½	30	21	21	19	−0.292	0.414	9.8	7.4
2	227	4.6	4.1	41	43	31	33	26	0.122	−0.108	9	10.4
3	180	2.9	4.1	39	41	34	35	33	−0.292	0.414	13.4	10
4	227	4.6	4.1	59	58	50	50	46	0.122	−0.108	12.8	14.2

The effect of the distribution of loss on the temperature rise is shown in a very striking manner by the following figures taken from curves 9 and 10. See Table II.

Analysis of the temperature loss diagram. It has been pointed out in discussing the tests of Table I, that the final temperature of the stator copper after shutdown is approximately equal to the final temperature of the stator iron in any one test. Therefore, *o a*, Fig. 9, the temperature rise of the iron per kw. iron loss at the point where core loss = $I^2 R$ loss, must equal *o b*, Fig. 10, the temperature rise of the copper per kw. $I^2 R$ loss, at the same point.

If then *o b* can be predetermined, and also the slope of the copper line *c d*, Fig. 10, the iron line *e f*, Fig. 9, can be drawn in, because the copper and iron temperatures are about equal at any load.

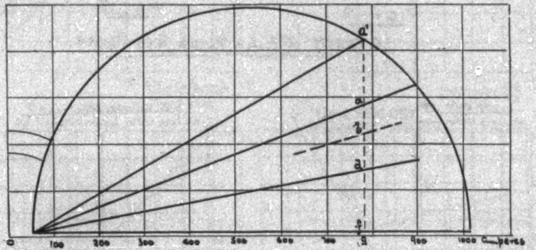


FIG – 11

The reason why it is desirable to predetermine *o b* rather than *o a* is that, as has been shown in Figs. 7 and 8, the copper loss is a more important factor in determining the temperature rise than is the iron loss.

Effect of a high resistance rotor on the stator temperatures. Table III gives four heat runs on a motor of construction similar to Fig. 5 and of the following dimensions:

D = 33 in.

λ_1 = 7½ in. The machine has a 0.5-in. vent duct in the center of the stator and rotor cores.

λ_2 = 17.25 in.

~ = 60 cycles.

p = 12 poles.

synchronous rev. per min. = 600.

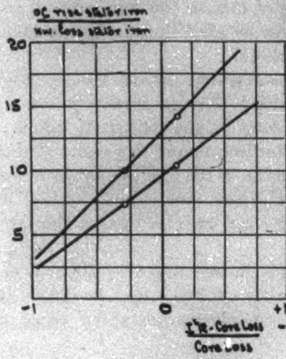


FIG- 12

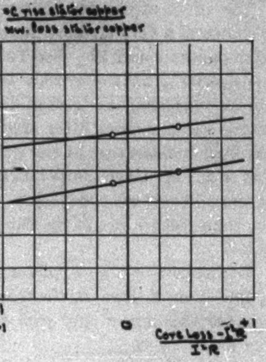


FIG- 13

EFFECT of HIGH ROTOR RESISTANCE

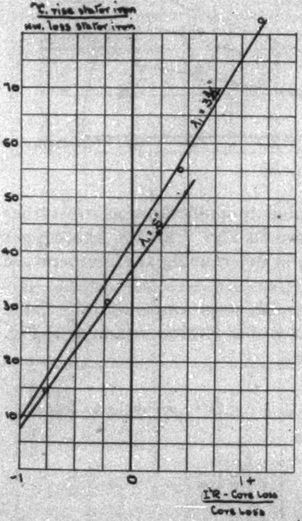
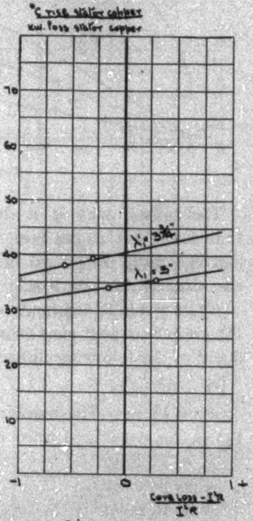


FIG- 14



Machine - 14½" dia.

FIG-15

This machine was tested with two different sets of rotor end connectors, all other things being unchanged. The effect of the change in the end connectors may be seen from Fig. 11, where

a b = the rotor end connector loss at the lock point in tests 1 and 2, Table III.

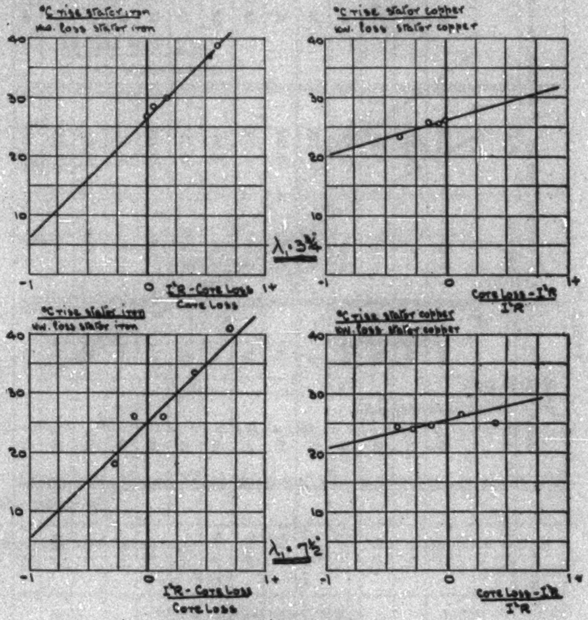


FIG-16 Machine-20' dia. FIG-17

*a*¹ *b* = the rotor end connector loss at the lock point in tests 3 and 4, Table III.

b d = the rotor bar loss, which was unchanged.

These results are plotted in curves, Fig. 12 and 13, and show that with an increased rotor loss of 100 per cent there is an increase in temperature rise of 40 per cent.

TABLE IV.

D''	λ_1''	λ_2''	Kw. stator loss		° cent. Stator temp. rise		I^2R – core loss	core loss – I^2R	temp. rise copper ° cent.	temp. rise iron
			I^2R	Core loss	Copper	Iron	core loss	I^2R	I^2R	core loss
14½	3¾	11⅞	0.72	0.5	28½	27½	0.44	–0.305	39½	54
"	"	"	1.15	0.5	44	41½	1.3	–0.56	38	83
"	5	12⅜	0.7	0.9	25	28	–0.22	0.29	35½	31
"	"	"	0.96	3.2	40	45½	–0.67	2.34	42	14.2
"	"	"	1.12	0.9	38	39	0.245	–0.196	34	43.5
20	3¾	11⅞	0.69	0.67	18	18	0.005	–0.003	26	26.8
"	"	"	0.71	0.67	19	18	0.06	–0.056	25.3	28.4
"	"	"	1.08	0.67	26	26	0.61	–0.38	23.2	38.8
"	"	"	0.93	0.8	24	24	0.175	–0.15	25.7	30
20	7½	16½	1.37	1.2	34	31½	0.142	–0.124	24.7	26
"	"	"	2.04	1.2	50	49½	0.7	–0.41	24.5	41
"	"	"	0.93	1.3	23½	23½	–0.285	0.4	25	18
"	"	"	1.6	1.15	38½	38½	0.39	–0.28	24	33.5
"	"	"	1.6	1.8	43	47	–0.11	0.125	26.5	26

Effect of changing the length of machine. The tests in Table IV, were made on four machines built as in Fig. 5; the dimensions of these machines are shown under columns D, λ_1 and λ_2.

The results of these tests are plotted in curves Fig. 14 and 15 for the machines 14.5 in. diameter, and Fig. 16 and 17 for the machines 20 in. diameter. These latter curves are plotted separately for the two lengths of machine because they lie so nearly on the top of each other.

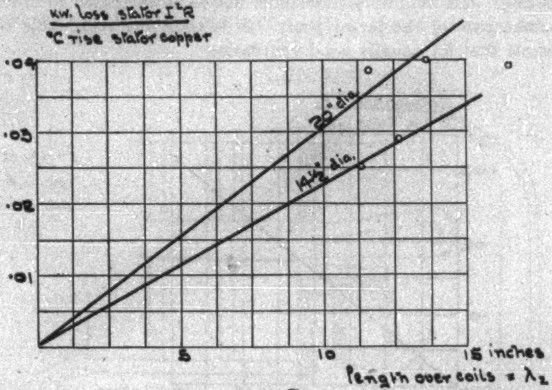


FIG.-18

From Figs. 15 and 17, at the point where core loss = stator I^2R, the value of

$\frac{\text{deg. cent. rise stator copper}}{\text{kw. loss stator copper}}$	D	λ_1	λ_2	$\frac{\text{kw. loss stator copper}}{\text{deg. cent. rise stator copper}}$
40.5	14½	3¾	11⅜	0.025
34.5	14½	5	12⅝	0.029
26	20	3¾	11⅞	0.0385
25 see table VII	20	5½	13⅝	0.04
25.5	20	7½	16½	0.0393

These results are plotted in the curve shown in Fig. 18.

It will be noted in the case of the 14.5 in. diameter machine that $\frac{\text{kw. loss stator copper}}{\text{deg. cent. rise stator copper}}$ is directly proportional to λ_2.

In the case of the 20-in. machine, however, the ratio is nearly constant, that is, there is nothing gained, so far as heating is concerned, by lengthening the machine.

There is a reason for this, however, which adds interest to the results. In the 14.5-in. machine the same bearings and fans are used on both lengths. In the 20-in. machine, on the other hand, as the machine is lengthened, the size of the bearings is increased, and thereby the air inlet is diminished in size. The fans have to be made smaller in order to clear the larger bearing housings, and the hub of the spider has to be increased in order to take care of the larger shaft. It is therefore reasonable to assume that for equally good ventilation

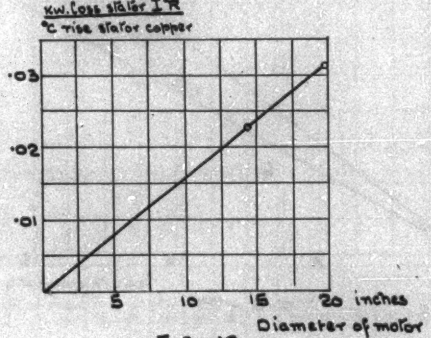


FIG.-19

$$\frac{\text{kw. loss stator copper}}{\text{deg. cent. rise stator copper}}$$

is directly proportional to λ_2.

Effect of changing the diameter of machine. From the curve in Fig. 18, assuming a constant length over the coils $= \lambda_2 = 10$ in.

$$\frac{\text{kw. loss stator copper}}{\text{deg. cent. rise stator copper}} = 0.0225 \text{ where } D = 14.5 \text{ in.}$$

$$0.031 \quad \text{"} \quad D = 20 \text{ in.}$$

These two figures are plotted in curve Fig. 19 from which it will be seen that:

$$\frac{\text{kw. loss stator copper}}{\text{deg. cent. rise stator copper}} \text{ is directly proportional to } D.$$

Effect of the diameter of bearing. It has already been suggested in the case of the 20-in. diameter machine that the size of the bushing may affect the heating to some extent.

The following tests bear this out.

A machine with dia. $D = 17$ in., $\lambda_1 = 13.5$ in. with four 0.5-in. vent ducts, $\sim = 25$ cycles, $p = 4$, was tested first with a set of bearings 3 in. by 9 in. and again with a set of bearings 4 in. by 10 in. the fans and spider hub being unaltered, with the following results:

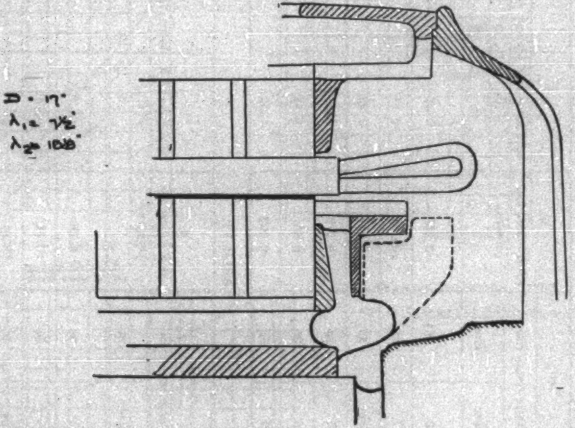


FIG. - 20

Bearings	Kilowatt stator loss		Temp. rise in deg. cent.	
	Copper	Iron	Copper	Iron
3 by 9	1.8	2.3	43	39
3 " 9	2.78	2.3	58	53
4 " 10	1.8	2.3	49	45.
4 " 10	2.78	2.3	65.5	57

TABLE V.

~	Syn. r.p.m.	Kw. stator loss		° Cent. Stator temp. rise		$\frac{I^2 R - \text{core loss}}{\text{core loss}}$	$\frac{\text{core loss} - I^2 R}{I^2 R}$	$\frac{\text{temp. rise copper ° cent.}}{I^2 R}$	$\frac{\text{temp. rise iron ° cent.}}{\text{core loss}}$
		$I^2 R$	Core loss	Copper	Iron				
25	750	1.06	1.4	40	36½	−0.242	0.32	37.5	26
"	"	0.975	1.15	37	32½	−0.152	0.18	38	28.5
"	"	0.815	1.4	33½	32	−0.417	0.72	41	23
40	1200	0.91	1.1	27	25	−0.173	0.208	29.5	22.7
60	1800	0.97	2.8	25	25	−0.65	1.88	25.8	8.9
"	"	1.38	2.8	32	32	−0.505	1.02	23	11.4

TABLE VI.

~	Syn. r.p.m.	Kw. stator loss		° cent. Stator temp. rise		$\frac{I^2 R - \text{core loss}}{\text{core loss}}$	$\frac{\text{core loss} - I^2 R}{I^2 R}$	$\frac{\text{temp. rise copper ° cent.}}{I^2 R}$	$\frac{\text{temp. rise iron ° cent.}}{\text{core loss}}$
		$I^2 R$	Core loss	Copper	Iron				
25	750	1.24	1.05	25	24	0.18	−0.153	20.2	22.8
"	"	1.95	1.05	39	34	0.86	−0.46	20	32.5
"	"	0.18	2.1	10½	16	−0.91	10.7	58	7.6

The increase in temperature rise, due to the use of the larger bearings and shaft, is 14 per cent.

Effect of peripheral speed on heating. A machine of the dimensions shown in Fig. 20 was run under the following conditions shown in Table V.

The above tests were made without the rotor fans which are shown dotted. These results are plotted in curves Fig. 21 and Fig. 22.

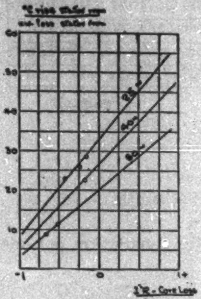


FIG-21

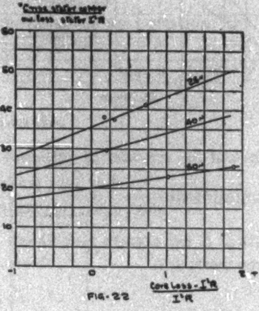


FIG-22

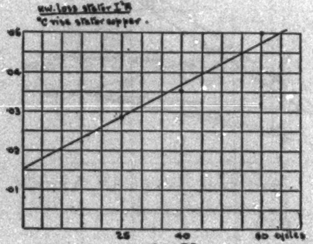


FIG-23

TESTS on an INDUCTION MOTOR

RUN at DIFFERENT FREQUENCIES

From curve Fig. 22 at the point where $I^2 R$ = core loss, we have

$$\frac{\text{deg. cent. rise stator copper}}{\text{kw. loss stator } I^2 R} = \begin{array}{l} 20 \text{ for } 60 \text{ cycles.} \\ 28.5 \text{ `` } 40 \text{ ``} \\ 35.5 \text{ `` } 25 \text{ ``} \end{array}$$

or the reciprocal, viz.:

$$\frac{\text{kw. loss stator } I^2 R}{\text{deg. cent. rise stator copper}} = \begin{array}{l} 0.05 \text{ for } 60 \text{ cycles.} \\ 0.035 \text{ `` } 40 \text{ ``} \\ 0.028 \text{ `` } 25 \text{ ``} \end{array}$$

These latter results are plotted in Fig. 23, which curve shows that the heat is got rid of by radiation and by convection; the former is independent of the speed of the machine; the latter is directly proportional to speed.

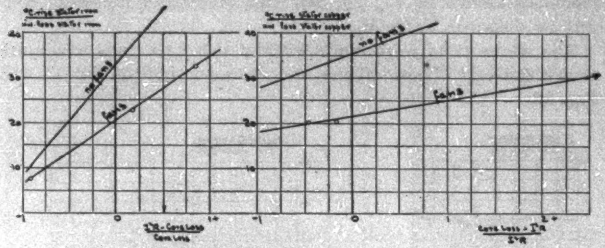


FIG-24

To find the constant of radiation.

$$\text{At standstill } \frac{\text{kw. loss stator } I^2\,R}{\text{deg. cent. rise stator copper}} = 0.015.$$

Watts $I^2\,R$ per square inch taken care of by ventilation per one degree cent. rise.

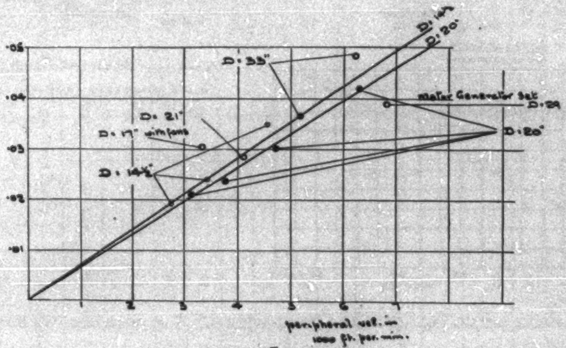


FIG-25

The radiating surface of the machine is taken as

$$\pi \times \text{diameter} \times \lambda_2 = \pi \times 17 \times 18\tfrac{1}{8} = 970 \text{ sq. in.}$$

therefore,

deg. cent. rise per watt $I^2\,R$ per sq. in. radiating surface

$$= \frac{1 \times 970}{0.015 \times 1000} = 65 \text{ deg. cent.}$$

This value has been checked on other diameters and lengths of machine.

Effect of fans on heating. The same machine was supplied with sheet metal fans as shown by the dotted lines, Fig. 20, with the results as shown in Table VI.

These results are plotted in curves in Fig. 24.

General summary of results. Table VII gives a summary of the tests already quoted. The table is self-explanatory, and the results are plotted in the curve in Fig. 25.

Expressing the results in the form of an equation, the temperature rise of an induction motor similar to Fig. 5, at the point where the stator $I^2 R$ loss = stator core loss, is given by:

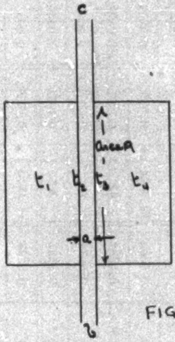


FIG-26

Watts $I^2 R$ for 1 deg. cent. rise

$$= \frac{1000}{N} = \frac{1000}{M} + \frac{1000}{Q}$$

$$= \frac{\pi D \lambda_2}{65} + 0.0065 \times V \times \pi D \lambda_2$$

$$= \underline{\pi D \lambda_2 (0.015 + 0.0065 V)}$$

where V = peripheral velocity in 1000 ft. per min.

This equation determines $o\,b$, Fig. 10, and $o\,a$, Fig. 9.

TABLE VII·

Poles	~	Syn. rev. per min.	D	λ_1	λ_2	$\pi D \lambda_2$	Radiation from motor at rest		Heating under load conditions		Effect of ventilation		Peripheral velocity	Remarks
							Assume 65° cent. rise per watt I^2R per sq. in.						in ft. per min.	
							$M =$	$\frac{1}{M}$	N	$\frac{1}{N}$	$\frac{1}{Q} = \frac{1}{N} - \frac{1}{M}$	$\frac{1}{Q} \times \frac{1000}{\pi D \lambda_2}$		
							°cent. rise per kw. I^2R radiated = $\frac{1000 \times 65}{\pi D \lambda_2}$	Kw. I^2R radiated per 1° cent. rise	°cent. rise per kw. I^2R loss = $o\,b$ Fig. 10	Kw. I^2R loss per 1° cent. rise	Kw. I^2R loss taken care of by ventilation per. 1° cent. rise	Watts I^2R per sq. in. taken care of by ventilation per 1° cent. rise		
6	60	1200	14½	5	12⅝	575	113	0.0088	34.5 fig. 15	0.029	0.0202	0.035	4560	
8	"	900	"	"	11⅝	530	122.5	0.0082	48	0.0209	0.0127	0.024	3420	
10	"	720	"	"	11⅜	517	126	0.0079	56	0.0178	0.0099	0.019	2750	
6	"	1200	20	3¾	13½	850	76.5	0.0131	20.5	0.049	0.0359	0.042	6300	
8	"	900	"	5½	13⅝	860	76	0.0132	25.5	0.0392	0.026	0.0304	4730	
10	"	720	"	6½	14¼	900	72	0.0139	28.5	0.035	0.0211	0.0235	3780	
12	"	600	"	3¾	10⅞	685	95	0.0105	40	0.025	0.0145	0.0211	3150	
10	"	720	33	4½	15⅛	1570	41.5	0.0241	10	0.1	0.0759	0.0485	6220	
12	"	600	"	5½	15½	1610	40.5	0.0246	12	0.083	0.0584	.0.0363	5200	
8	"	900	29	7¼	19¼	1750	37	0.027	10.5	0.095	0.068	0.039	6820	2 bearing motor generator set 3½ in. vent ducts
4	25	750	21	9½	23¼	1535	42.5	0.0235	15	0.067	0.0435	0.0284	4130	4½ in. vent ducts.
4	"	"	17	7½	18⅛	970	67	0.0149	22.5	0.0445	0.0296	0.0305	3330	Fig. 20 with fans.

It is still necessary to determine the slope of line *c d* for a complete determination of the temperature rise.

In Fig. 10 *g c* is the value of the deg. cent. rise of the stator copper per kw. stator $I^2 R$ at the point where the core loss = 0. This quantity varies from 70 per cent to 90 per cent of *o b*, depending upon the rotor resistance, construction and size of machine; a good guess based on results of similar machines is the easiest way to determine it.

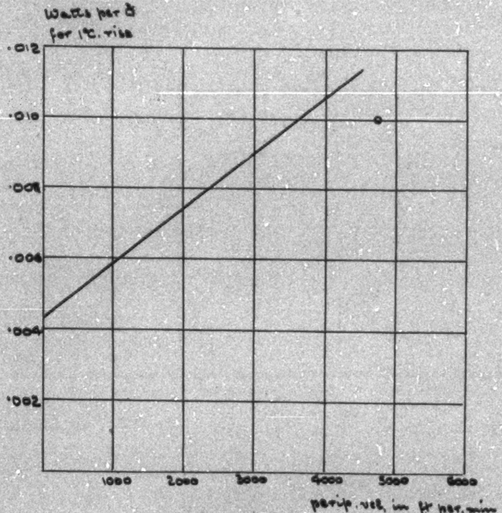


FIG-27

Heating of induction motors totally enclosed. Before discussing this subject the following digression will prove instructive. If *c b*, Fig. 26, be a plate of metal through which heat is passing from, say, steam at one side at a temperature t_1, to water at the other side at a temperature t_4, the flow of heat being steady, then if the plate be not too thick k = the thermal conductivity $= \dfrac{Q a}{A (t_2 - t_3)}$

Where Q = the quantity of heat passing through the plate per sec.
a = the thickness of the plate.
A = the area of the plate.
t_2 and t_3 = the temperatures of the two sides of the

plate. This quantity k was measured by three different experimenters who gave the following values: Clément 0.0057, Péclet 0.178, Angström 1.1,

The-last mentioned result is now recognized as being correct, and the cause of the great discrepancy is of interest in connection with the heating of enclosed machines.

Clément assumed that $t_1 = t_2$ and $t_3 = t_4$. He had steam at the one side at a temperature of 100 deg. cent. and water at the other side at a temperature of 28 deg. cent. He assumed that $t_2 - t_3 = 100 - 28 = 72$ deg. cent., whereas we now know it was only 0.36 deg. cent.

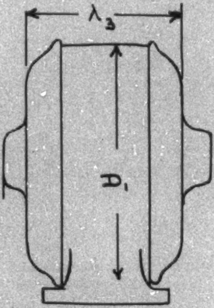


FIG. 28

Péclet improved on Clément's method by putting stirrers in the two chambers, by which means he got 32 times as much heat through the plate; that is, stirring brings the temperature t_1 more nearly equal to t_2, and t_3 more nearly equal to t_4.

It will therefore be seen that ventilation, or stirring up the air, is of as much importance in an enclosed motor as it is in the open type of machine.

In curve, Fig. 27 is plotted the result of a number of tests on a line of well-ventilated direct-current enclosed motors; also one test on a squirrel-cage induction motor, similar to Fig. 5. The radiating surface used to determine the value of watts per sq. in. is that of the total external surface of the frame. It equals

$$\pi D_1 \lambda_3 + \frac{\pi D_1^2}{2}$$

The temperature rise is that of the armature or stator coils.

TABLE VIII

D = 20 in. p = 8 poles. External Radiating Surface = 3260 sq. in.
λ_1 = 5½ in. ~ = 60 cycles.
λ_3 = 13⅝ in. periph. vel. = 4730 ft. per min.

Losses
stator I^2R = 0.77 kw.
rotor I^2R = 0.9 "
stator core loss = 0.77 "
total loss 2.44 kw.

Heat runs temperature rise given in ° cent.

Standard motor Fig. 5	Same motor	Same motor	Same motor	Parts of motor
	Housing holes closed with perforated sheet metal ⅜" holes on ⅝" centres	Housing holes closed with sheet metal	Housing holes closed with sheet metal	
	Yoke openings A. open	Yoke openings A. open	Yoke openings A. closed with cardboard	
18½° cent. rise	22° cent. rise	46° cent. rise	74° cent. rise	Stator coils
18½	20	48	71	" laminations
15	21	46	71	Rotor cond.
14	21	44	71	" ring
14	20	41	69	" laminations
14	24	39	61	Oil in bearings
		25–30	52–57	Outside of yoke

The following figures, in Table VIII, show how nearly uniform the temperature becomes in the inside of such a machine. It is not the purpose of this paper to enter into the subject of the use of open motors with large sheet-metal cases, or the use of forced ventilation or water cooling, yet there is room for valuable discussion on this point.

Discussion on "The Heating of Induction Motors."
Frontenac, N. Y., June 28, 1909

Theodore Hoock (by letter): In calling attention to the large losses in the motor while the motor is starting, Mr. Gray is apt to give the squirrel-cage motor a worse reputation than it merits. It is true that the losses at the moment of starting are very large, but it is also true that these losses decrease rapidly as soon as the motor is under way. I believe that the squirrel-cage motor can sometimes be used under quite serious starting conditions where a wound secondary motor would be objectionable, as the amount of the starting losses at the first moment proves by no means a serious obstacle. In considering a proposal involving rather severe starting conditions, I proceeded as follows:

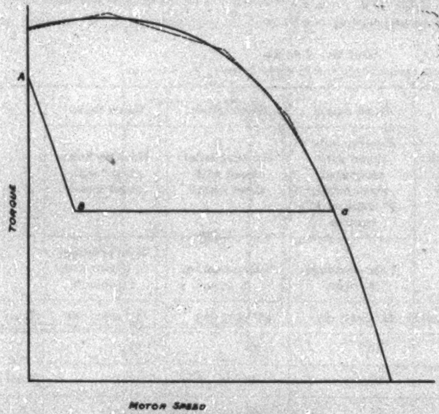


Fig. 1—Speed-torque curve.

The speed-torque curve of any motor can be replaced approximately by a number of straight lines, as shown in Fig. 1. From the total torque, the load torque, represented by the straight line *B C*, should be subtracted. Also a liberal allowance for the friction of rest should be made for the first part of the starting period, as indicated by the line *A B*. By subtracting the load and friction torque from the total torque, we obtain the curve of the torque available for acceleration, as shown in Fig. 2.

For each of the straight line parts, the following relations apply, see Fig. 3. The equation for any of the lines is

$$T = T_1 + \frac{T_2 - T_1}{v_2} v \tag{1}$$

We know further

$$d v = p \, d t \tag{2}$$

where $d v$ is the change of speed during the time $d t$ and p is the acceleration, we find

$$p = \frac{T}{m} = \frac{T g}{w}$$

where

m = mass to be accelerated.
w = weight " "
g = acceleration of gravity.

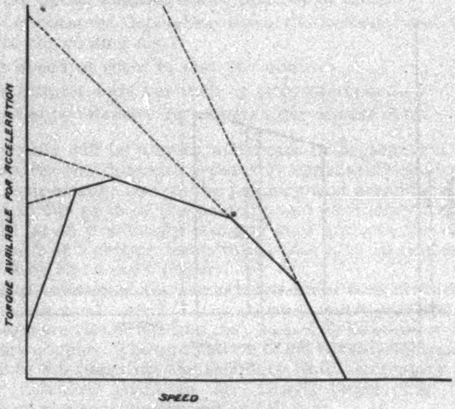


FIG. 2.

By combining equations 1, 2, and 3, we obtain the following differential equation,

$$d v = \left(T_1 + \frac{T_2 - T_1}{v_2} v \right) \frac{g}{w} d t$$

From this we obtain by integration,

$$t = \frac{w v_2}{g (T_2 - T_1)} \; l n \left[\frac{T_1 + \frac{T_2 - T_1}{v_2} v}{T_1 + \frac{T_2 - T_1}{v_2} v_1} \right]$$

For cases where the torque decreases, the following form of the formula is more convenient,

$$t = \frac{w\,v_2}{g\,(T_1 - T_2)}\ ln\left[\frac{T_1 - \dfrac{T_1 - T_2}{v_2}\,v_1}{T_1 - \dfrac{T_1 - T_2}{v_2}\,v}\right]$$

For constant torque, we obtain of course,

$$t = \frac{(v - v_1)\,w}{T\,g}$$

The speed-time curves can be directly calculated from these formulas.

From the motor characteristics it is possible to plot a curve showing the relation between losses and speed. From such a curve, and the speed-time curve, a curve giving the losses at any time during the starting period may be plotted. When starting is not frequent, it is sufficient for one start to figure the heating of the various parts from the heat capacity of the parts under the assumption that no cooling takes place during the starting period. This assumption will of course give somewhat too high values, so the figures will be on the safe side. When the starting is frequent, the time-loss curves of the starting period may be used in combination with the curves for the running periods for figuring the continuous average losses. Figuring this way, it will be found in many cases that the heating is not at all serious. By properly designing the motors for the purpose, it has been possible to use squirrel-cage motors; for

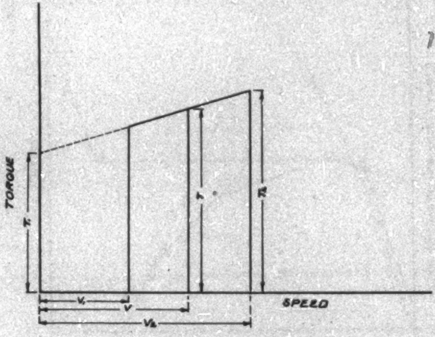


FIG. 3.

Mr. Gray's tests show that the temperature rise of the primary copper is virtually independent of the iron losses. This has been my experience. I use a very simple method of estimating the temperature rise of an induction motor without knowing the dimensions of the winding.

The temperature rise of the primary copper can be found by the equation

$$T_1 = T_0 + \frac{F_1}{F_{vent} \times \left(1 + \frac{v}{1970}\right)} \times A\,S_1 \times S_1$$

T_0 = Temperature-rise at primary copper losses = 0.
F_1 = A constant largely depending upon the type and secondary losses; further upon length of iron, ventilating ducts, insulation and number of poles.
F_{vent} = A constant depending upon the velocity and volume of the cooling air.
v = Speed of rotor in feet per minute.
$A\,S_1$ = Ampere bars per inch of circumference.
s_1 = Copper density in amperes per square inch.

This formula will be a great assistance in beginning a design, as it compares the different types and ventilating devices.

If the temperature rise of the primary and secondary copper is plotted in the ratio of the primary and secondary losses, the points will lie on practically straight lines and cut the ordinate at watts = 0 at a certain temperature rise 3 to 10 degrees cent. (see Fig. 8 of Mr. Gray's paper).

For the calculation of the secondary copper temperature-rise a similar method can be used. In most cases of low-voltage motors the temperature rise of the iron may be said to be equal to that of the primary copper. The application of blowers allows an increase of from 2 to 3.5 times in the primary and secondary losses. For the machine given in Mr. Gray's paper, Fig. 20, the temperature rise may be figured as follows:

Assume for 1 kw. primary losses $A\,S_1 = 500$ $s_1 = 1800$ amperes per square inch.

$F_{vent} = 1$ without blowers.

$$25 \text{ cycles } T_1 = 10 + \frac{81.10^{-6}}{1\,(1+1.64)}\, 0.500 \times 0.1800 = 37.6° \text{ cent.}$$

$$40 \text{ cycles } T_1 = 10 + \frac{81.10^{-6}}{1\,(1+2.71)}\, 0.500 \times 0.1800 = 29.7° \text{ cent.}$$

$$60 \text{ cycles } T_1 = 10 + \frac{81.10^{-6}}{1\,(1+4.06)}\, 0.500 \times 0.1800 = 24.4° \text{ cent.}$$

with fans

$$25 \text{ cycles } T_1 = 10 + \frac{81.10^{-6}}{2.1\,(1+1.64)} 0.500 \times 0.1800 = 23^\circ \text{ cent.}$$

It was tested $37.5^\circ - 28.5 - 25^\circ$ cent.

F_{vent} has been increased 100 per cent.

For high-voltage machines with heavy insulation, special attention should be paid to the *highest* temperature rise of the copper which is generally in the center of the core. The proposed temperature rise of 85 per cent, if measured on the coil-ends, seems to be far too high for cotton insulation.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

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REDUCTION IN CAPACITY OF POLYPHASE MOTORS DUE TO UNBALANCING IN VOLTAGE

BY S. B. CHARTERS, JR. AND W. A. HILLEBRAND

It is well-known that polyphase motors of both induction and synchronous types overheat when supplied from circuits in which the ideal conditions of voltage balance and phase angle are not maintained. In order to determine definitely the performance under other than ideal conditions, and to ascertain the points at which overheating commences, a series of tests were made under varying conditions of voltage unbalance, unsymmetrical angular relations between phases, and combinations of these two.

The authors have not attempted to analyze the performance under these conditions in any but the most elementary manner, and are able only to present the results of their tests with such comment as will bring out the essential features developed.

The equipment for the test consisted initially of a laboratory motor built by one of the leading companies; this was a 7.5 h.p., six-phase motor, capable of operating either as a two-phase or three-phase machine. The terminals of all phases were brought to an external connecting block or tablet and all inter-connections were made there. On this motor the first series of tests were made in order to determine the essential features of the performance, and were then followed by characteristic runs on several different commercial machines. The principal data of the machines tested are given in Table I.

Power was supplied by a two-phase 60-kw. inductor alternator, with voltage regulators in each phase, through two 10-kw. multitap transformers. Three phases were obtained from the two-phase supply by means of the Scott connection. By the use of the voltage regulators and various taps on the transformers any desired degree of unbalance could be obtained. When operating two-phase, the phase angle of one of the applied pressures was shifted by combining with it pressure from a quadrature source, as shown in Fig. 1. This connection also unbalanced the voltage as well, but, when desired, the two voltages could be brought to equality by means of regulators at the generator.

From any three-phase star or delta connection wherein the vector sum of the electromotive forces is zero, it is impossible to obtain unbalanced voltages without a shift of the phase angle as well, so that in the three-phase runs no attempt was made to separate these factors.

TABLE I.

Machine	h.p.	No. of phases	Rotor	Voltage	Frequency	Connection
Laboratory model as induction motor........	7½	2	squirrel cage	190	60	
Laboratory model as induction motor........	7½	3	squirrel cage	127	60	delta
Laboratory model as synchronous motor...	7½	2		310	60	
Commercial induction motor...............	10	2	squirrel cage	200	60	
Commercial induction motor...............	5	3	squirrel cage	220	60	Y
Commercial induction motor...............	2	3	squirrel cage	110	60	delta(?)
Commercial induction motor...............	5	3	Wound rotor with internal starting resistance	110	60	delta (?)

One set of instruments, especially calibrated for this test, was used throughout. Instruments were applied to one phase at a time and then shifted to the next, two or more sets of readings being taken from each phase, the second serving as a check and to insure that conditions did not change during the time the readings were being taken.

The motors were loaded by belting to a separately excited direct-current generator.

The operating limit of a motor, as determined by the temperature rise in any one phase, is reached when the current in that phase has attained its normal full-load value. Throughout these tests the motor was loaded under varying conditions of voltage unbalance and phase shift until the normal rated current was reached in one phase, when the output at that point was determined. Curves were then plotted showing the relation between the output at this point and the percentage of voltage unbalance and irregularity of phase difference. The voltage in the high phase was maintained at normal value throughout. The per cent. of voltage unbalance is defined as the difference between maximum and minimum voltages divided by the maximum, whether operating two-phase or three-phase.

In the test with the laboratory model, delta connected, it was found, on comparing the currents in the motor winding and in the lead wires, that with a condition of unbalance represented by two voltages high and of approximate equality and one voltage low, the current in the lead wire and that in the motor itself reached normal value at the same time, regardless of the percentage of unbalance. This fact was made use of in operating the two 110-volt, three-phase motors, for, not knowing whether they were connected Y or delta, we had no other means of determining when the current in the motor winding had reached normal value. Accordingly the motors were assumed to be delta connected and operated with two voltages high and one low, and, on the basis of the performance of the laboratory model, it was assumed that when normal current was reached in one of the lead wires one phase of the motor winding was also

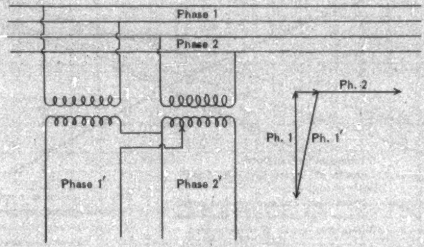


FIG. 1.

carrying normal rated current. As indicated by Fig. 2, the motor would probably not behave very differently under any other condition of unbalance.

That the performance is practically independent of the nature of the voltage unbalancing, whether this takes the form of two voltages equal and the other higher or lower, or of all three at different values, is well brought out in Fig. 2, which shows the results of tests made upon a three-phase, Y-connected motor under all three conditions. This point, however, we do not regard as settled, because with our laboratory set delta connected, an appreciable difference has been observed between the performance with one voltage high and two low, and that with two high and one low, the latter being somewhat the worse condition. The difference, however, is not enough to alter the results materially, and we have not been able to determine as yet whether it is due to the fact that this is a special machine or whether it is more or less common to all motors.

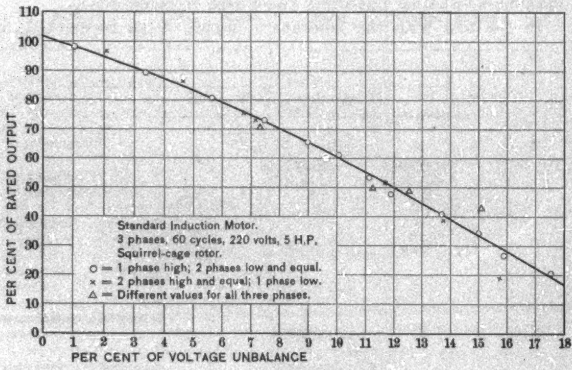
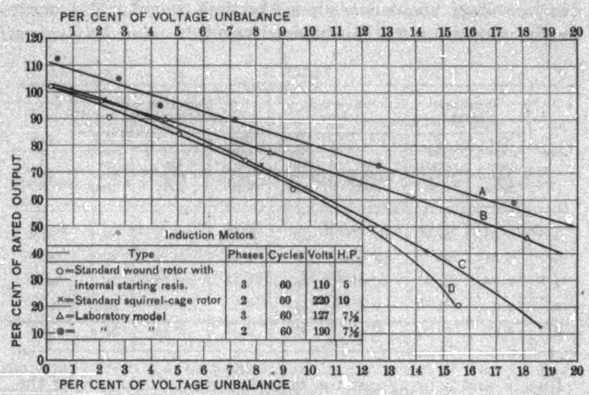


Fig. 2.

The extent to which reduction in capacity is caused by voltage unbalancing is strikingly brought out by Figs. 2, 3 and 4. We wish particularly to call attention to the practical identity of the curve of Fig. 2 and curves *C* and *D* in Fig. 3, which represent the performance of three commercial motors differing in ype, voltage or rating, in which a voltage unbalance of 10 per cent caused a reduction in capacity of 40 per cent.

The worst performance of all is shown in Fig. 4, which is that of a 2-h.p. three-phase 110-volt motor in which an unbalance of 10 per cent caused a reduction in capacity of 54 per cent or 44 per cent, according to which curve is used. On the name plate 13.7 amperes was given as the full-load current, whereas our test, with balanced voltage, showed 11.1 amperes at the rated output of 2 h. p.

Voltage unbalance, however, is not the only factor to be considered in the case of two-phase motors, for departure of the supply voltages from the quadrature relation, or phase shift, has an even greater effect. By measurement it was found that our generator gave practically true quadrature phases under all conditions of unbalance, the difference being less than 0.5 degree, so that the results from voltage unbalance alone are not complicated by phase shift.



Type	Phases	Cycles	Volts	H.P.
○=Standard wound rotor with internal starting resis.	3	60	110	5
×=Standard squirrel-cage rotor	2	60	220	10
△=Laboratory model	3	60	127	7½
●= " "	2	60	190	7½

FIG. 3.

The extent to which phase shift causes reduction in capacity is shown in Fig. 5, where in the one commercial motor tested a departure of 5 degrees from the quadrature relation caused a loss in output of 26 per cent.

Next to the extent to which reduction in capacity is caused by voltage unbalance or phase shift, the most significant fact is that the reduction seems to vary with either irregularity approximately according to a straight line law. With a combination of the two, however, in the case of a two-phase motor, the effect seems to be cumulative and certainly worse than the sum of the two individual results. This is indicated by the results given in Table II.

In cases 1, 2 and 3 the laboratory model was operated as a two-phase motor. Cases 4 and 5 were for the commercial 10-h.p. two-phase motor, and furnish evidence along the same line, though the result is not so striking for the reason that, at the particular values used, the effect due to phase shift greatly exceeded that due to voltage unbalance, which therefore contributed a much smaller proportion to the combined result.

TABLE II.

Case	Unbalance alone		Phase shift alone		Unbalance and shift combined			Sum of *A* and *B*
	Per cent unbalance	*A* Per cent reduction	Degrees shift	*B* Per cent reduction	Per cent unbalance	Degrees shift	Per cent reduction	
1	5.38	16.2	10° 1′	20	5.38	10° 1′	50.2	36.2
2	9.05	27	14° 9′	30	9.05	14° 9′	72.7	57
3	8.16	24.3	21° 37′	42	8.16	21° 37′	98.7	66.3
4	2.1	3	5° 27′	31	2.1	5° 27′	36.9	34
5	4.38	10.5	6° 49′	38	4.38	6° 49′	52.4	48.5

Figs. 3 and 5 bring out the fact that the performance of the laboratory model with either voltage unbalance or phase shift was much superior to that of the commercial motors. For instance, with 10 per cent voltage unbalance its capacity was reduced 30 per cent as against 40 per cent for three commercial motors, and with a 5-degree phase shift the figures are 10 per cent for the laboratory model and 26 per cent for the commercial motor. By reference to Fig. 6 it will be seen that the efficiency of the laboratory model is about 3 per cent lower than the average of the efficiencies of the four standard motors. With greater proportions of unbalance and phase shift the difference in favor of the special machine is even greater. This shows in convincing manner how design may affect performance under other than ideal conditions.*

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* See Appendix A.

It should be borne in mind that in all the foregoing tests the voltages recorded are those at the motor when operating with full-load current in at least one phase, and that they do not represent line conditions, no account having been taken of transformer regulation or voltage drop in the lead wires.

The effect of transformer regulation is to improve the conditions at the motor, for our experiments showed that the high phase always furnished the heaviest current, which would mean a greater reduction in the voltage of that phase, tending to bring the motor voltages to equality. In the three-phase motor the effect of transformer regulation is not so easy to foresee, because one phase can not be altered without affecting both of the others. However, it appears from observations made to determine this point that the three-phase case does not differ materially from the two-phase, in the tendency of transformer regulation to improve conditions of unbalance at the motor. The results of these observations are given in Table III.

TABLE III.

No load			Full load in one phase		
Voltage in high phase	Voltage in low phase	Per cent unbalance	Voltage in high phase	Voltage in low phase	Per cent unbalance
115.42	91.22	20.95	109.45	91.67	16.52
115.17	97.17	15.61	110.75	97.02	12.4
113.6	100.25	11.76	109.47	99.05	9.52
115.65	108.65	4.475	110.32	105.37	4.48

In this run the primary voltage was held constant under both no-load and full-load conditions.

These figures must be understood as applying to a particular case, because the inherent regulation of our transformers, as connected, was poor. However, the results may be doubtless taken as indicating the general effect of transformer regulation. It is the line unbalance at no load which is responsible for the performance of the motor, so that this performance will be largely dependent on local conditions. If the motor is operated from its own individual transformers the regulating effect will be much greater than if it is only one of a large number of motors supplied from transformers of large capacity on which the effect of any individual motor will not be appreciable. Therefore, in a large shop driven by polyphase motors supplied from a common set of transformers, if unbalance exists the performance of the motors will be much better when all are running than when only a few are in operation.*

The improvement due to transformer regulation means a general lowering of voltage, most of which, however, takes place in the high phase. The general lowering of voltage means a reduction in the capacity of the motor, but this is more than counter-balanced by the improvement in the condition of unbalance which enables each phase to approach more nearly its proper share of the power. For example, in our laboratory set a 20 per cent unbalance at the motor with normal voltage in the high phase means a reduction in capacity of about 65 per cent. Assuming a transformer regulation which would give 15 per cent unbalance at the motor, the reduction in capacity would be only 43 per cent, provided the voltage in the high phase could be maintained at normal. If this 15 per cent unbalance at the motor is accompanied by a 10 per cent reduction in the voltage of the high phase, with a corresponding reduction in the other phases, the additional reduction in capacity is only

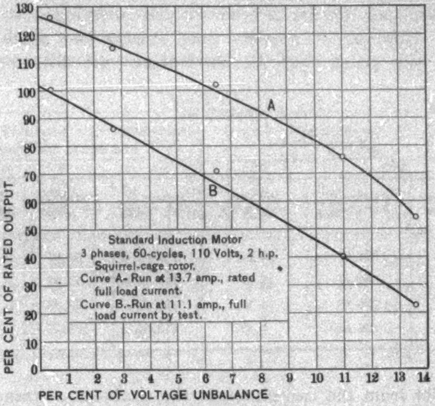

FIG. 4.

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* See Appendix B.

6 per cent, as shown by curve *C*, Fig. 7, giving a total of 50 per cent reduction for a combined 15 per cent unbalance and 10 per cent reduction below normal of the voltage in the high phase, as compared with 65 per cent reduction in capacity for 20 per cent unbalance, normal voltage being maintained in the high phase.

Curve *C*, Fig. 7, shows the reduction in output or torque in the laboratory set, operating three phase and delta connected, as the voltage is lowered at a uniform unbalance of 14.8 per cent, current being maintained at normal value in the high phase. This unbalance of 14.8 per cent is the ratio of the difference between maximum and minimum voltages divided by the maximum voltage and not by normal voltage. Curve *A*, Fig. 7, shows results obtained with the same motor under conditions of balanced voltage, and curve *B* those obtained under conditions of balanced voltage but with a different motor.

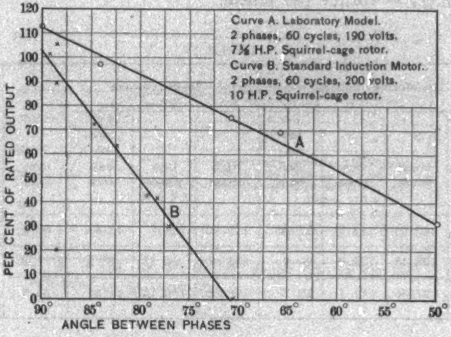

FIG. 5.

Curves *A* and *B* would represent the performance due to line drop, with balanced voltage. Curve *C* would approximately represent the performance of a three-phase motor with unbalanced voltage as affected by line drop alone, for the observations recorded in Table IV indicate that with a three-phase motor the line drop does not tend to improve materially the conditions of unbalance.

With the two-phase motor the effect of line drop is similar to that of transformer regulation, improving the conditions of unbalance at the motor, since the higher phase, where reduction is most needed, invariably furnishes the most current.

Curves *A* and *B*, Fig. 7, are of interest in their bearing on the commonly accepted statement that the torque of an induction motor varies as the square of the voltage. This is true provided the slip remains constant. If the slip is allowed to vary and the current held constant, the torque will be found to vary with the first power of the voltage, and this condition is the one usually found in practical operation. The familiar torque equation is

$$Q_p = k \; \frac{s \, r_2 \, E}{r_2^2 \;\; s x_2^2} \qquad (1)$$

wherein Q_p = torque per phase.

TABLE IV.

Transformer voltage				Motor voltage				Motor voltage
Intermediate phase	High phase	Low phase	Per cent unbalance	High phase	Low phase	Per cent unbalance	Per cent load	Intermediate phase
112.7	130.0	112.0	13.88	115.95	101.1	12.81	83.6	104.9
102.4	128.45	102.0	20.6	113.95	90.25	20.8	71.8	97.4
127.3	127.35	111.1	12.7	120.05	106.15	11.53	69.3	116.25

k = a constant, depending upon units in which torque is expressed.
r_2 = secondary resistance.
x_2 " reactance.
E = primary induced e.m.f.
s = slip.

also

$$s = i_2^2 \; \frac{r_2 k}{Q_p} \qquad (2)$$

wherein i_2 = secondary current.

Substituting the equivalent of *s* from equation 2 in equation 1, and reducing,

$$Q_p = k \, i_2 \sqrt{E^2 - i_2 x_2^2}$$

Keeping i_2 constant, this equation represents approximately a straight line, as borne out by the results shown in Fig. 7. Holding the primary current constant, the secondary current will also be nearly constant, a slight change being introduced by the decrease in magnetizing current with the drop in pressure, but not enough to affect materially the straight line relation of torque and voltage.

SYNCHRONOUS MOTOR

The test on the synchronous motor was performed in exactly the same manner as on the induction motor except for the fact that the field excitation of the synchronous motor was adjusted at every observation so as to give minimum current in the high phase under the existing conditions.

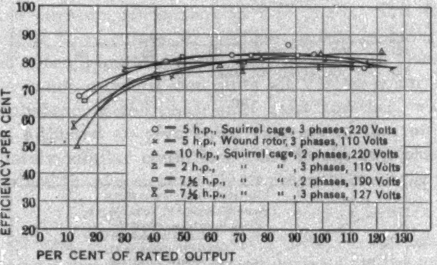

FIG. 6.

The results obtained with the synchronous motor are submitted not on account of their quantitative value but because of the indication they afford of the manner in which synchronous motors and converters behave when supplied from unbalanced circuits.

We wish to call attention to the striking similarity between synchronous and induction motor performances in that the reduction in capacity due to either phase shift or voltage unbalance varies in both cases approximately according to a straight line law, and that shift of phase is a much more serious factor than voltage unbalance. (See Fig. 8.)

The synchronous motor, however, differs materially from the induction motor in its behavior under conditions of combined

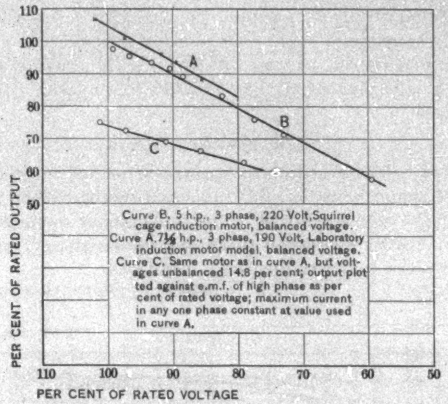
110
100
90
80
70
60
50
A
B
C
Curve B. 5 h.p., 3 phase, 220 Volt, Squirrel cage induction motor, balanced voltage.
Curve A. 7½ h.p., 3 phase, 190 Volt, Laboratory induction motor model, balanced voltage.
Curve C. Same motor as in curve A, but voltages unbalanced 14.8 per cent; output plotted against e.m.f. of high phase as per cent of rated voltage; maximum current in any one phase constant at value used in curve A.
PER CENT OF RATED OUTPUT
110
100
90
80
70
60
50
PER CENT OF RATED VOLTAGE

FIG. 7.

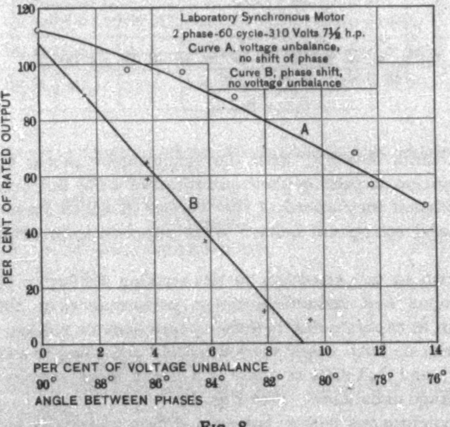
Laboratory Synchronous Motor
2 phase-60 cycle-310 Volts 7½ h.p.
Curve A. voltage unbalance, no shift of phase
Curve B. phase shift, no voltage unbalance
A
B
120
100
80
60
40
20
0
PER CENT OF RATED OUTPUT
0
2
4
6
8
10
12
14
PER CENT OF VOLTAGE UNBALANCE
90°
88°
86°
84°
82°
80°
78°
76°
ANGLE BETWEEN PHASES

FIG. 8.

phase shift and voltage unbalance, in that the two effects seem to neutralize one another, and an improved performance may result, as shown in Table V.

TABLE V.

Synchronous Motor Performance.

Unbalance alone	Reduction in capacity	Phase shift alone; degrees	Reduction in capacity	Sum of reductions	Effect of combined unbalance and phase shift
8.4%	34%	4.0	48%	82%	42%
3.6%	11%	2.1	24%	35%	10%

In general, the effect of voltage unbalancing is to circulate a quadrature current component in one phase. The effect of phase shift is to circulate an in-phase current in both phases, one phase often pumping back into the line. In either case, one phase takes most, if not quite all, of the power. When voltage unbalancing and phase shift exist together, with field excitation adjusted to give equal currents in the two phases, approximately similar conditions exist in the two phases and each is enabled to take more nearly its proper share of the power.*

SUMMARY AND CONCLUSIONS

Summarized briefly, the results of our tests are the following:

1. Unbalancing of voltage and shift of phase tend to cause serious overheating in polyphase motors.

2. Where it is possible to separate the effects due to phase shift and voltage unbalance, phase shift is found to be relatively of more importance.

3. The reduction in capacity due to either phase shift or voltage unbalance varies with the cause approximately according to a straight line law.

4. In the induction motor the existence of phase shift and voltage unbalance causes a worse performance than would be expected from either irregularity alone, whereas in the synchronous motor the reverse may be the case.

5. The performance of the induction motor supplied from an unbalanced circuit is materially affected by its design.

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* See Appendix C.

6. The commonly accepted statement that the torque of an induction motor varies with the square of the voltage should be changed to read, " varies directly with the voltage," in order to make it more consistent with conditions of ordinary operation.

The authors hope that this paper will promote further investigation and discussion of the subject of line unbalance, which is continually increasing in importance as transmission lines increase in the amount and variety of service which they furnish.

APPENDIX A

An induction motor will endeavor to carry the load put upon it, regardless of the condition of supply voltage, so it is important to know not only what load the motor will carry with a given amount of unbalance without overheating in any phase, but also what the effect will be upon the motor if it is forced to carry full load when supplied from unbalanced circuits.

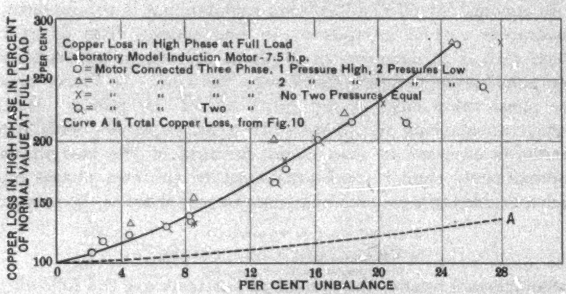

FIG. 9

Fig. 9 shows for the laboratory model, the ratio of copper loss in the phase which carries the high current under varying conditions of unbalance, when the motor is delivering its rated load, to the copper loss at full load with balanced voltage. With this motor an unbalance of 10 per cent means a 50 per cent increase in copper loss in one phase, and with a good commercial motor the increase would probably be greater. As shown in Fig. 10, however, the total increase in copper loss for moderate unbalancing is not serious.

APPENDIX B

Transformer Regulation—Open Delta

An exception to the statement that the effect of transformer regulation is to improve conditions at the motor should be made in the case of three-phase service from two transformers connected as an open delta. When supplying current to a balanced, non-inductive load the power-factor in each of the two transformers, assuming balanced primary voltages, is 86.6 per cent, leading in one transformer and lagging in the other. The regulation in each transformer is different, with consequent unbalancing and circulation of unequal currents to bring the voltages back to approximate equality.

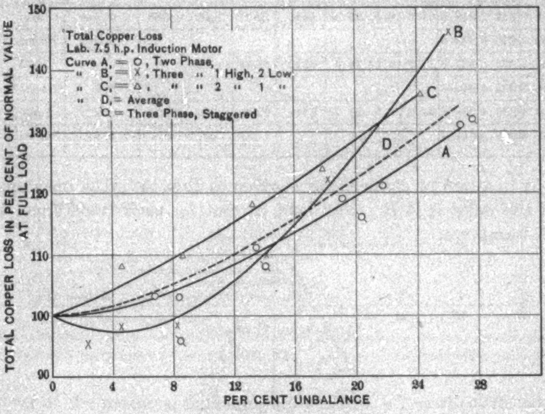

Fig. 10.

When supplying current to induction motors operated at, say 85 per cent power-factor, the phase-angle of the current in each transformer is shifted about 30 degrees. One transformer is operating now at almost unity power-factor and the other at a power-factor of about 50 per cent. When the pressures are unbalanced, if the transformer with inherently the higher power factor has also the higher voltage and current, the impedance drop in each transformer may be about the same, the low power-factor of one compensating for the heavier current in the other, with little or no improvement in the conditions of unbalance. This is illustrated in Table VI.

TABLE VI

Volts			Amperes			Watts		Power-factor		Per cent unbalance	
A C	*B C*	*A B*	*A*	*B*	*C*	*A C-A*	*B C*–B	*A C*	*B C*		
226.0	224.3	222.5	25.8	26.3	27.2	6055	3435	1.04	0.583	1.55	Load
233.6	230.2	232.1								1.45	No load
226.3	197.2	211.3	24.4	13.9	25.7	5670	1660	1.03	0.606	12.9	Load
232.6	202.4	220.0								13.0	No load
225.0	212.2	218.6	23.6	18.5	25.35	5440	2300	1.02	0.586	5.7	Load
230.1	216.8	223.8								5.8	No load
244.8	225.5	232.9	24.6	18.95	25.9	6240	2520	1.04	0.59	7.9	Load
248.8	232.4	244.3								6.6	No load
246.4	229.4	235.8	24.0	17.5	25.2	6140	2280	1.04	0.568	6.9	Load
251.9	230.9	244.4								8.33	No load

A diagram of connections is given in Fig. 11. The open side of the delta is *A B*. Full load current for each transformer is 45.4 amperes.

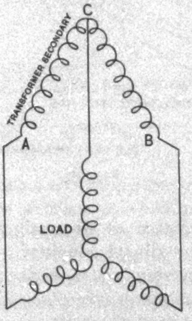

Fig. 11.

APPENDIX C

Synchronous Motor

In Fig. 12 is shown the performance on unbalanced voltage of the same motor connected three phase. The scattered location of some of the points is in part to be accounted for by the fact that the current in the high phase was not exactly the same for all observations, the points above and below curve *B* corresponding in general to values of high and low current. The conditions of unbalance were chiefly two pressures high and one low with two or three staggered values, for the transformer regulation was so great that we could not get one pressure high and the other two low with the motor loaded.

After each observation with the motor loaded, the motor was immediately disconnected and the line pressures at no load were read to determine the effect of transformer regulation, or the power of the motor in balancing up the line. The effect in this case is extreme because our particular transformers when transforming two-phase to three-phase, to furnish 220 volts at the secondary, regulate poorly. Curves *A* and *B* may be of interest, however, as showing the balancing effect in a particular case. The capacity of the motor was somewhat less than half the combined capacity of the transformers from which it was supplied.

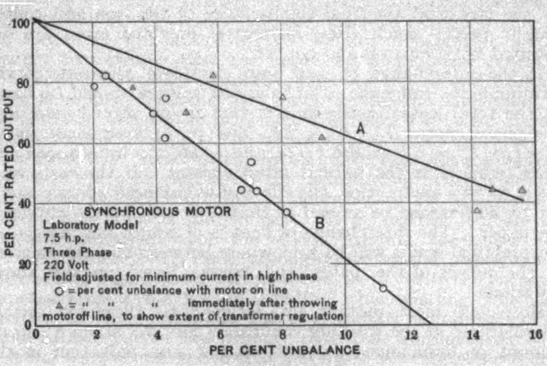

FIG. 12.

That the chief regulating effect was in the transformers was shown by reading generator pressure with the motor on and off the line. The change in generator pressure with load was small.

DISCUSSION ON "REDUCTION IN CAPACITY OF POLYPHASE MOTORS DUE TO UNBALANCING IN VOLTAGE." FRONTENAC, N. Y. JUNE 28, 1909

R. E. Hellmund (by letter): All of the interesting figures regarding the harmful effect of unbalanced voltage upon the rating of polyphase motors given in this paper are based on the assumption that the largest current in any of the phases should not be larger than the rated full-load current. This assumption would lead to correct conclusions if there were no interchange of heat between the various parts of the stator; it is my experience, however, that there is a comparatively free interchange of heat between the various stator parts. This is brought out by the fact that the final temperature of the iron and coils is usually pretty much alike, no matter how the losses are distributed between iron and copper.

If the interchange of heat were complete, the tests for determining the influence of unbalanced voltage should be based on the total losses in the stator; that is, we should have in a two-phase motor $I_1^2 + I_2^2 = 2\,I^2$, and in a three-phase motor $I_1^2 + I_2^2 + I_3^2 = 3\,I^2$ where I_1, I_2, and I_3 are the unbalanced currents, while I is the normal rated current. If the tests were based on this assumption, the effect of unbalanced voltage would not by any means be as bad as that indicated by the curves in the paper. The interchange of heat is of course not perfect, so the practical result will be somewhere between the values given by the curves of the paper and curves based on the above equations.

Moreover, most motors are designed to allow for certain irregularities in the working conditions, and will stand a certain amount of unbalanced current without any reduction in the rating. Another thing that tends to reduce the danger caused by unbalanced currents is that the amount of unbalancing usually decreases with the load. It is, therefore, the smallest for the overloads; that is, for the condition for which increased heating through unbalancing is the least desirable.

It is well to mention these facts, for it is just as undesirable to overestimate harmful effects as it is to underestimate them. Overestimating harmful effects would induce an engineer to go to an expense out of proportion to the value of the results obtained thereby. Nevertheless I agree that unbalanced currents in polyphase motors are undesirable. In certain extreme cases they are even dangerous to the motor. If possible they should be avoided. As mentioned in the paper, the amount of unbalancing in the current depends not only upon the unbalancing of the voltage but also upon the design of the motor. The question arises, therefore, whether an attempt should be made to obtain motors that give for a certain unbalancing of the voltage a minimum unbalancing of the current. This question may be answered by the following considerations.

The current of an induction motor may be considered to consist of three parts: 1. The load current. 2. The leakage reactance current. 3. The no-load reactance current. It is the latter current that is chiefly affected by unbalanced voltages. This may be best explained by referring to a single-phase induction motor. In this type of motor a field is induced by the primary in the direction of the primary-coil axle, while certain secondary currents in the light running motor carry the field around and induce also a field at right angles to the first axle. At no load the size of this field at right angles is only a few per cent smaller than the primary field, the difference being chiefly caused by the ohmic drop in the secondary. If, therefore, the primary is provided with a second winding equal to the energizing winding, but at right angles thereto, the field carried around by the secondary will induce in this winding a potential only a few per cent smaller than the impressed single-phase potential and shifted 90 degrees against it. If upon the second primary there is impressed a potential which is opposite and equal to the potential induced by the secondary, there will be no current in this second winding. The motor can now be considered to be a two-phase motor with unbalanced potentials impressed; and it will be seen that while the unbalancing of the potential is only a few per cent, the unbalancing of the magnetizing current is as much as 100 per cent. If we further decrease the potential impressed upon the second winding, the motor will furnish current to the line through this second phase, which then acts as a generator. If, however, we increase the potential impressed upon the second winding, this winding will take current, and the current in the two primary windings will be equal as soon as the two primary potentials are equalized.

It has been shown above that a 100 per cent unbalanced condition is obtained if the unbalancing of the potential is equal to the ohmic drop of the secondary. This means that for a given unbalancing of the primary currents the unbalancing of the primary potentials may be the larger, the larger the ohmic drop in the secondary. In other words, the tendency for unbalanced magnetizing currents in the primary may be decreased only by increasing the secondary resistance.

It is at once obvious that this means should not be used as a remedy, since the increased losses caused thereby in the secondary are more harmful than the usual unbalancing of the total primary current. The unbalancing in the load current and the leakage reactance current is not quite so serious as that of the magnetizing current. Moreover, I do not think the design of the motor has much influence on it. It might be suggested that since the no-load magnetizing current is chiefly affected by the unbalanced voltage, the unbalancing of the total current may be kept small by designing the motors for small magnetizing currents. While this is true, it is hardly of any importance in this connection, since the designer always reduces for other reasons the magnetizing current as far as other considerations allow.

I have considered in the above an unbalancing in the intensity of the voltage only. The consideration of the case of incorrect phase displacement leads to similar conclusions. In this case the unbalancing of the current may be reduced by increasing the primary resistance and leakage reactance, while both of these factors should be kept small for other more important considerations. I believe it is usually safe to say that any unbalancing effect can be only reduced by adding resistance or reactance somewhere in the motor circuit; that is, by harmfully affecting the motor performance in other respects.

It appears, therefore, that the only remedy that may be applied to unbalanced currents in the motors is to improve the line conditions. Precaution is advisable regarding the statement made by the authors of the paper about the influence of the potential upon the torque of induction motors. It is stated in the paper that the torque is directly proportional to the potential; this statement is based on the assumption that the size of the current alone is limiting the motor rating. It should be remembered, however, that if the potential decreases, the core losses decrease also, and therefore larger copper losses and a larger current are allowable. For this reason it is difficult to make any correct statement concerning the continuous torque rating. The usual statement, that the torque is proportional to the square of the potential, applies only to the starting torque and the maximum torque, and is approximately right for these cases.

A. E. Averett: I do not think that the statements made in Conclusion 6 are correct. The ordinary condition of operation in the case of induction motors is at constant voltage. The torque of an induction motor is proportioned to the square of the voltage.*

Regarding the balancing of induction motors; I have found the same thing in a number of tests. I would express it in terms perhaps a little different, as follows: a motor with 15 per cent unbalanced voltage will heat almost double what it would at normally balanced voltage. It operates very much as it would single phase, (in which case the maximum output of the motor would be about 40 per cent of the three-phase) plus a supplemental quadrature component.

A. M. Dudley: I do not understand the conditions under which the writer wishes us to assume that the torque varies directly as the voltage; for under the conditions ordinarily met with, I think it is true that the torque varies as the square of the voltage. In the usual conditions of operation the current is not regulated, but automatically adjusts itself as the load is varied. For this reason the torque will certainly vary as the square of the voltage.

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*See Steinmetz "Alternating Current Phenomena," p. 248.

John C. Parker: I wish to call attention to the commercial phases of the feature of unbalancing brought out in the paper. Where isolated industrial plants are used the distribution is almost always by means of conduits wherein line conditions do not obtain to unbalance the voltage, and wherein heavy single-phase loads are not carried in the plant to unbalance the voltage. Where long-distance power transmissions are used there is a possibility of unbalancing of the phases. With central station companies the same thing almost always occurs, owing to the carrying of lighting loads and single-phase motor loads. As a matter of experience, this current unbalancing in the different phases of induction motors has been found to be quite serious. Many of the transmission companies selling hydroelectric power incorporate into their contracts a clause requiring the balancing of the loads taken by the different phases; under such conditions, if a heavy motor load is carried and the voltage is unbalanced, the user of the power may be penalized by virtue of that fact. The motor struggles to deliver uniform counter electromotive force on all the phases, the line does not do equally well, and the difference must be made up in the circulating of wattless currents in some phases of the motor. So much for the matter of the purchase of power from a transmission line.

Taking the case of the ordinary distributing companies, distributing to retail customers. In the effort to improve the load-factor, most of the central station companies are adopting a basis of power sale in which the customer having the better load-factor receives the better rate. To determine what the maximum demand is, some form of indicator is used. Up to the present date the most commonly used maximum indicator is a meter or indicator depending on the heating effect of the current. The meter takes no cognizance whatever of the circulating current taken by the motor in its struggles to maintain mormal conditions, as to whether the circulating current is in one direction or the other. If the maximum demand meter unfortunately happens to be in the phase taking the high current, the customer is penalized; if in the phase taking the lower current, the company suffers. If maximum demand indicators are installed in all phases and read once a month, the conditions may change between readings, so once a month a customer might still be penalized as the meter records only the maximum demand which has been pulled.

I am aware, as we all are, that there are now under development maximum demand meters not depending on the current drawn by the line, but again the commercial consideration comes in that it is very desirable to penalize the customer whose demand is at a poor power-factor, and hence there are strong commercial reasons why a maximum demand wattmeter rather than a maximum demand ammeter should be employed. Hence we do not get away from the difficulty introduced by the fact that an unbalance of the phase angles or of the voltage produces a deviation from balance in the current which is all out of proportion to the cause. This brings home very significantly the importance to distributing companies of keeping their load balanced as far as possible, and, where that is not possible, of the balancing of voltage by single-phase rather than by polyphase potential regulators.

Charles P. Steinmetz: In reading this paper I was astonished by the statement that the torque of the induction motor varies directly in proportion to the voltage, until I found the cause of this mistake in the assumption that the current must not exceed a definite maximum value. The torque of the induction motor varies with the load, so that in considering the relation of the torque to the voltage or anything else it is necessary to state what torque is meant. There may be under consideration the maximum torque of the motor; that is, the torque where the motor drops out of step and comes to a standstill. Or it may be the torque that the motor can maintain continuously with constant heating, the safe heating of the motor. Both torques are important. The maximum torque of the induction motor varies with the square of the voltage. To send a three-phase locomotive over a long-distance railway with twenty per cent drop in the line, trusting that the maximum decrease of torque in an emergency will be only twenty per cent, will result in disappointment, because the maximum torque drops with the square of the voltage. Again, the torque which the motor can maintain continuously at constant heating does not vary proportionally to the voltage, nor proportionally to the square of the voltage, because the heating depends not only on the current but also on the magnetic flux, that is on the voltage. If the voltage is increased, with the same current, the losses, and thereby the temperature, are also increased; to maintain the same temperature the current must be lowered correspondingly, while at lower voltage the current can be raised. It will be found, then, that for the same heating of the motor the maximum torque which the motor can carry varies with the voltage. The torque is greatest at a certain definite voltage, while at a lower voltage as well as at a higher voltage the torque which the motor can give with the same heating, is less.

Applying this to the case of unbalanced voltage: if the voltage in one phase is high and in the other low, the energy loss is shifted in the copper by raising one current and lowering the other, and also to some extent the losses are shifted in the magnetic field, and the simple relation given in the paper does not hold true; but it will be found that at constant heating the permissible motor-torque is decreased only very little by an unbalancing of voltage. A considerable unbalancing of voltage must occur before the torque is appreciably decreased at the same heating, or the heating is increased at the same torque.

These relations of the torque to voltage and unbalancing, as determined by the heating of the motor, are still further complicated by the design of the motor, because not merely the total energy loss counts, but local heating must be considered. In one motor the loss of power in the coils may be more objectionable, because the heat cannot escape rapidly through the coil insulation. In another motor the coils and the iron may, through the entire range, maintain practically the same temperature; for instance, in a low-voltage motor. Therefore the relation is a more complicated one than appears at first sight; it depends on the design of the motor, the character of the insulation, its thickness; that is, on the voltage for which the motor is intended, etc. But speaking broadly, we must say that *the maximum torque of the motor varies with the square of the voltage*; that the *safe heating torque is a maximum at some definite voltage*; that the *unbalancing of the voltage is relatively harmless*, up to a certain amount, but becomes objectionable and harmful only when excessive.

Chas. F. Scott: This paper takes up an important and interesting feature of the induction motor. The basis of comparison, however, in which the normal current from one of the motor circuits is taken as a standard of comparison, is not a proper standard of comparison for ordinary practical operation, as has been pointed out by several of the speakers. There would be some danger, therefore, in applying the results given in the paper promiscuously to average circumstances. The practical point in operation is to determine whether a motor operating on a commercial circuit is getting into difficulty, and is going to have its safe operating conditions exceeded by an unbalancing in voltage. The safe capacity of the motor is not determined by the current through one of its circuits. That does not determine its temperature. Sometimes the heating of the motor is not the limit. It may be the regulation, the starting conditions, or something else. Some induction motors run at very low temperatures, so that a considerable unbalancing would not lead to an excess in the temperature conditions. The motor not merely receives more energy on one circuit than on the other, but it may act as a transformer. Synchronous motors and induction motors upon an operating circuit tend to lessen unbalancing between phases and hence have an equalizing effect.

That motors differ among themselves in their characteristics should be taken into account before applying the results of this paper to every condition. Motors differ not only in their temperature distribution, but also in various other characteristics. When acting as an equalizer between unbalanced circuits a large motor or one which is a poor transformer may not have any trouble in equalizing, whereas a little motor or one which is an efficient transformer may overexert itself. The summary of my comments is that the tests, while interesting, are based on certain laboratory conditions which do not permit their indiscriminate application to practice.

H. L. Wallau: Referring to unbalanced voltage, I have in mind some readings taken in a case of trouble. A 110-volt, three-phase motor had been connected to a circuit consisting of two transformers arranged in open delta, one of them, however, cut over to a secondary voltage of 230 volts, and the other to 115 volts, so that the voltage applied to the motor was 230 volts across one phase and 115 volts across another phase, and 200 volts across a third phase. When this motor was started on its load, the voltage dropped in one phase from 230 to 220, in another from 200 to 196 volts, and jumped from 115 volts to 122 volts in the third phase. It confirmed the fact that motors will work as transformers when the supply voltage is unbalanced and fed back into the line.

S. B. Charters, Jr.: The only point I wish to make is in regard to the matter of torque. We probably did not make clear what we meant. Our idea was this: a man is operating a motor under such load that he is drawing practically the limiting current of the motor as far as heating goes. If, under these conditions the voltage is reduced, the torque of the motor will be reduced; that is, provided each time the full-load current is considered as the limiting factor. As the voltage goes down, less torque will be developed; it will vary approximately as a straight line loss, as far as our results go, as represented in Fig. 7, curves A and B. However, as has been said, to a certain extent these are laboratory results, and that should be taken into consideration before applying them to commercial circuits.

As stated by Mr. Scott, the difficulty in starting is an important point, because it was a case of that kind which first drew our attention to the difficulties introduced by unbalancing. In a plant operating three-phase, certain motors at considerable distance from the transformers would not start without the rest of the plant, because under the conditions of unbalancing which existed at the plant they were unable at times to develop enough torque to start under load. With the plant operating, the other motors balanced these conditions so that these motors would operate. When they were operating alone they were unable to affect the transformer conditions sufficiently and were not able to start.

I. E. Hanssen (by letter): The results obtained by the authors of the above paper agree closely with observations made by others, as may be seen by comparing the results obtained with the value given on the attached curve Fig. 1 which shows results of tests on a fairly large commercial motor. Of course, different motors will behave differently, depending upon the ease with which heat is conducted from the hottest places to the cooler ones.

It should be borne in mind that in the majority of cases the amount of unbalancing existing in well designed circuits is very small. A very small number of cases of trouble are reported from this cause. The writer believes it would be a serious mistake to build motors designed to minimize the effect of voltage or phase unbalancing by increasing the impedance of the windings, as such motors would have a low maximum torque, low starting torque, low starting efficiency, and probably low power-factor as well. All that is necessary and desirable is to take all reasonable precautions to prevent unbalancing of the circuits; that is, all conductors should be arranged as nearly symmetrical as possible and unbalanced transformer connections such as open △ and two-phase—three-phase, should be avoided whenever possible.

It goes without saying that motors which are themselves unbalanced should not be tolerated.

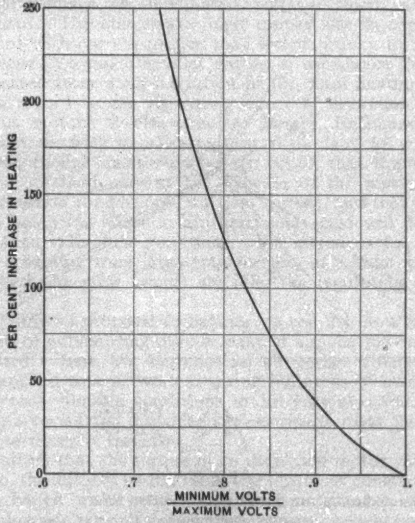

Fig. 1.

Such inherent unbalancing of a motor may be due to an unequal number of turns in the different phases, improper angular displacement between phases, or to unsymmetrical end-connections, the existence of none of these causes being justified.

That circulating currents may easily be of such magnitude as to be very objectionable, will be seen from the following. Take the case of a machine which has two or more parallel circuits per phase displaced from each other by say 10 electrical degrees. Then the voltage tending to set up circulating currents will be approximately $2E \sin 5$ degrees $= 0.174\,E$, when E is the impressed electromotive force.

Assuming the short-circuit current at rated voltage to be six times full-load current, then the circulating current will be about equal to one-half the full-load current.

If the impedance of a motor and its supply circuit are known, it is a simple matter to determine approximately the amount of unbalancing for any given load and voltage or phase unbalance. As an illustration Fig. 2 shows a graphical method applied to a three-phase motor.

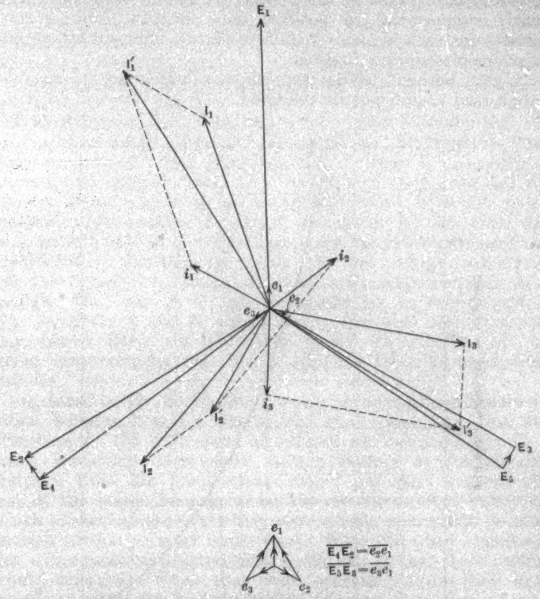
E1
I1'
I1
i2
i1
e1
e2
e3
I3
i3
I2'
I3'
E3
E2
E4
I2
E5
e1
e3
e2
$\overline{E_4E_2} = \overline{e_2e_1}$
$\overline{E_5E_3} = \overline{e_3e_1}$

FIG. 2.

$E_1\ E_4\ E_5$ = unbalanced impressed electromotive forces
$E_1\ E_2\ E_3$ = three-phase counter electromotive forces of the motor
$I_1\ I_2\ I_3$ = full-load current on balanced circuit
$i_1\ i_2\ i_3$ = circulating currents due to e_1, e_2 and e_3
$I_1'\ I_2'\ I_3'$ = resultants of normal full-load current and circulating currents

The circulating currents i_1 i_2 and i_3 are inversely proportional to the sum of the motor impedance and the circuit impedance per phase and lag behind their respective electromotive forces by angle $\tan^{-1}\phi = \frac{x}{-} = \frac{\text{rectance (inductive)}}{\text{resistance}}$

S. B. Charters, Jr. and W. A. Hillebrand (by letter): Those who have discussed this paper agree that unbalancing is undesirable, but carefully refrain from stating the point at which the consequences of this unbalancing may become serious. This point naturally depends upon the construction of the motor and the nature of its load, but the authors believe it to be reached earlier than most of those who have expressed an opinion seem willing to admit. Our belief is based upon the performance of motors which have burned out when operated steadily from regular commercial circuits that were unbalanced, and upon the showing of Fig. 9 and 10, printed in Appendix A. These represent the stator copper losses in the motor giving the best performance on unbalanced voltage, when carrying its rated load. The abnormally high copper loss in one phase is in accord with our experience, that serious injury to the motor may occur at a much smaller degree of unbalance than would be expected from a consideration of the total heating alone.

With regard to the regulating effect of induction and synchronous motors, dwelt upon by Messrs. Hellmund, Wallau, and Scott, we wish to call attention to the fact not emphasized by them, though mentioned by Mr. Scott, that this regulating effect is obtained only at the expense of the motor, through the circulation of additional wattless current, and that the extent of this balancing effect in any particular case will depend entirely upon individual conditions. For instance, if it is a small motor operating from large transformers at a time when other motors on the same circuit are idle, the regulating effect will be nil.

The offhand proposal to balance up the line as a remedy for the evils of unbalancing may be easy of application on a system of limited extent, but becomes an altogether different matter when applied to a network covering hundreds of miles, subject to different climatic conditions in its various parts, and furnishing a varied and miscellaneous service to meet the demands of the territory it traverses.

In stating that the torque of an induction motor varies as the voltage, the authors had in mind the torque at constant heating, which though of the greatest operating importance, is not commonly considered. Although our original contention may not be strictly correct, we feel that we have made our point in showing the necessity for stating which torque is referred to—that at starting, pull-out, constant or synchronous speed, or constant heating. In the first three cases the torque admittedly varies as the square of the voltage. It is the torque at constant speed which is referred to on page 248 of Steinmetz's *Alternating Current Phenomena*, referred to by Mr. Averett. This torque we do not consider, in general, to be of practical operating importance.

The torque at constant current varies approximately with the voltage. The iron losses vary about as the 1.6 power of the voltage. Therefore, below normal voltage the current and torque may be increased somewhat, and above normal voltage the current and torque must be decreased to some extent, to maintain constant heating.

Thus, below normal voltage the torque will vary somewhat less than the first power of the voltage, and above that point it will vary at a slightly lower rate. Throughout the operating range of any particular motor, however. we feel that our statement that the torque of the induction motor, for constant heating, varies as the first power of the voltage, is substantially true, and in support thereof quote from Dr. Steinmetz's contribution to the discussion to the effect that:

> It will be found, then, that for the same heating of the motor, the maximum torque which the motor can carry varies with the voltage.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

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THE CURRENT LOCUS OF THE SINGLE-PHASE INDUCTION MOTOR

BY A. S. LANGSDORF

The theory of the single-phase induction motor has, until recently, been complicated by the general use of Ferraris' expedient of resolving the impressed alternating magnetic field into forwardly and backwardly rotating components; this conception, though it leads to correct results if consistently handled, is open to the objection that it departs unnecessarily from the physical facts, and gives rise to the notion that the ordinary laws of electromagnetic induction are not immediately applicable, as in the direct-current machine. Within the last few years, however, the tendency in treating this problem has been to go back to first principles, and several valuable contributions have appeared, notably those of Fynn and McAllister. The following treatment has been based largely on the theory advanced by Fynn in his several publications.

I. *General principles and vector diagram.* The physical behavior of the single-phase induction motor having a permanently short-circuited or squirrel-cage rotor is identical with that of the motor shown diagrammatically in Fig. 1. This represents a stator of the usual cylindrical form with an embedded winding, and a wound rotor provided with a commutator. Two sets of brushes, short-circuited in pairs, are provided, the one set being magnetically in line with the axis of the stator winding, and the other at right angles thereto. Employing the usual nomenclature, the rotor axis $a\,a$ will be referred to as the "transformer" or "armature" axis, while the axis $f\!f$ will be called the "speed" or "field" axis. From the assumed construction of the magnetic circuit it follows that the reluctance will be the same along all axes, and that the resistance and leakage reactance of the rotor will be the same in both the transformer and speed axes.

Under standstill conditions the stator winding and the rotor winding along the axis *a a* constitute a short-circuited transformer whose magnetic circuit is " leaky " owing to the air-gap. But under any conditions, at standstill or when running, the usual transformer relations must be satisfied so far as this axis of the motor is concerned; the stator current must supply the magnetomotive force to produce the flux demanded by the impressed electromotive force (modified by the drop due to primary local impedance) and it must balance the magnetomotive force of the rotor current in the transformer axis. Thus, at standstill, if Φ_t, Fig. 2, is the flux of mutual induction in the transformer axis, there will be induced in both primary and secondary an electromotive force E_t lagging 90 degrees behind Φ_t (assuming unity ratio of transformation or that the secondary has been reduced to terms of the primary). A current i_t will then flow in the axis *a a* of the rotor, being determined in magnitude and phase by the local impedance of the rotor. The primary current, i_1, will then be the resultant of i_0, the magnetizing current, and of i_t reversed. The impressed electromotive force, E_1, will be the resultant of a component equal and opposite to E_t and of a component $i_1 z_1$ to overcome the local impedance, z_1, of the stator.

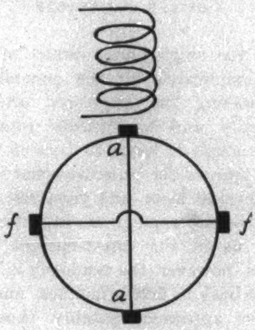

FIG. 1.

If the motor be brought up to speed in some way, there will be generated* an electromotive force $E_t{}'$ (Fig. 3) of line frequency, in the speed axis, ff. The magnitude of $E_t{}'$ will be proportional to Φ_t and the speed, and it will be either in time-phase with, or time-phase opposition to, the flux Φ_t, depending upon the direction of rotation. Let it be assumed to be in time-phase with Φ_t. The rotor current, i_t, in the transformer axis, also sets up a leakage field (ϕ_t) in phase with itself, stationary in space, and coaxial with Φ_t; hence there will also be generated in the speed axis an electromotive force $e_t{}'$, in time phase with i_t and proportional to ϕ_t and the speed. The resultant electro-

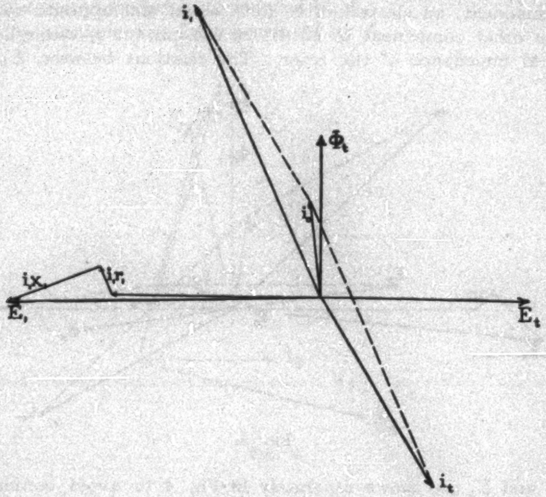

FIG. 2.

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* The following system of nomenclature has been used: Main fluxes are represented by (capital) Φ, with appropriate subscripts; leakage fluxes by ϕ. Electromotive forces *induced* by a main flux are capitalized and bear the same subscript as the inducing flux; electromotive forces *generated* by a main flux are capitalized and primed; electromotive forces due to leakage fluxes are similarly designated, except that lower case is used.

motive force in the speed axis is then E_f, compounded vectorially of E_t' and e_t'.

Inasmuch as the conditions along the speed axis are those of a transformer on open circuit, the electromotive force E_f will set up a current i_s lagging heavily, and this will produce a magnetic "speed field," Φ_s, nearly in quadrature with E_f. The speed field, by its alternation through the rotor winding, will induce in the speed axis an electromotive force E_s lagging behind Φ_s by a quarter period, hence E_f must contain, as one component, an electromotive force equal and opposite to E_s; the other component of E_f drives the current i_s through the local impedance of the rotor. The relations between E_f, i_s, Φ_s and E_s are shown separately in Fig. 4 to avoid confusion in Fig. 3.

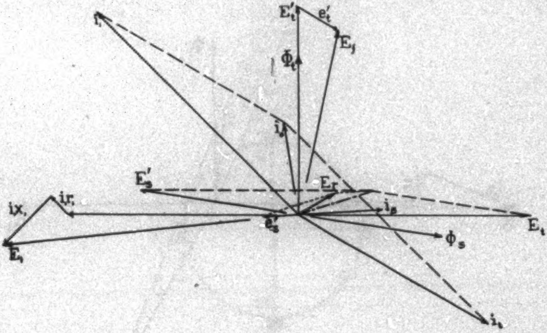

FIG. 3.

The motion of the rotor conductors through the speed field generates in the transformer axis an electromotive force E_s' which is in time-phase opposition to Φ_s, and, therefore, nearly opposed to E_t. E_s' is the equivalent of the counter electromotive force of the continuous-current motor. The speed-field current i_s also produces a small leakage flux (ϕ_s) coaxial with Φ_s and in time phase with i_s; hence there is a third electromotive force, e_s', in the transformer axis which is opposite in phase to i_s and proportional to ϕ_s and the speed. The electromotive force e_s' is small, but not necessarily neglible, especially near synchronism. The vector sum of E_t, E_s' and e_s', repre sented in Fig. 3 by E_r, then serves to drive the current i_t through the local impedance of the rotor.

II. Mathematical Treatment.

Collecting symbols, let

E_1 = primary impressed electromotive force.
i_0 = primary exciting current—rotor on open circuit.
i_1 = total primary current.
Φ_t = transformer flux.
Φ_s = speed flux.
E_t = electromotive force induced by Φ_t.
E_t' = electromotive force generated by Φ_t.

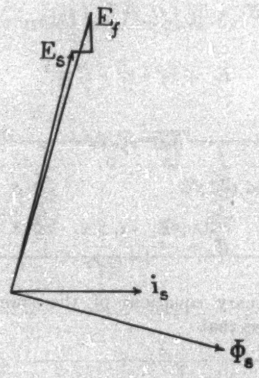

Fig. 4.

E_s = electromotive force induced by Φ_s.
E_s' = electromotive force generated by Φ_s.
i_t = rotor current in transformer axis.
i_s = rotor current in speed axis.
ϕ_t = leakage flux due to i_t.
ϕ_s = leakage flux due to i_s.
e_t' = electromotive force generated by rotation through ϕ_t.
e_s' = electromotive force generated by rotation through ϕ_s.
$z_1 = r_1 + j\,x_1$ = primary local impedance.
$z_0 = 1/y_1$ = primary exciting impedance.
$y_1 = g_1 - j\,b_1$ = primary exciting admittance.
$z_2 = r_2 + j\,x_2$ = secondary (rotor) local impedance.

$z_s = 1/y_2$ = secondary exciting impedance.
$y_2 = g_2 - j\,b_2$ = secondary exciting admittance (speed axis).
S = speed with synchronism as unity.

A little consideration will show that $e_t' = S\,x_2\,i_t$ and that $e_s' = S\,x_2\,i_s$ and that vectorially (see Fig. 3)

$$\underset{\cdot}{e_t'} = S\,x_2\,\underset{\cdot}{i_t} \tag{1}$$

$$\underset{\cdot}{e_s'} = -S\,x_2\,\underset{\cdot}{i_s} \tag{2}$$

From Figs. 3 and 4 it is seen that

$$\underset{\cdot}{E_t} = \underset{\cdot}{E_t'} + \underset{\cdot}{e_t'} = \underset{\cdot}{E_s} + \underset{\cdot}{i_s}\,z_2$$

or

$$\underset{\cdot}{E_s} = \underset{\cdot}{E_t'} + \underset{\cdot}{e_t'} - \underset{\cdot}{i_s}\,z_2 \tag{3}$$

But

$$\underset{\cdot}{i_s} = \underset{\cdot}{E_s}\,y_2,$$

hence from (1) and (3)

$$\underset{\cdot}{E_s} = \frac{\underset{\cdot}{E_t'} + \underset{\cdot}{i_t}\,S\,x_2}{1 + z_2\,y_2} \tag{4}$$

From the ordinary equations of the transformer and the generator it follows that

$$\begin{aligned} E_t &= \kappa\,\Phi_t \\ E_t' &= S\,\kappa\,\Phi_t = S\,E_t \\ E_s &= \kappa\,\Phi_s \\ E_s' &= S\,\kappa\,\Phi_s = S\,E_s \end{aligned}$$

where κ is a constant, and vectorially

$$\underset{\cdot}{E_t'} = j\,S\,\underset{\cdot}{E_t} \tag{5}$$

$$\underset{\cdot}{E_s'} = j\,S\,\underset{\cdot}{E_s} \tag{6}$$

From Fig. 3 there results

$$\underset{\cdot}{Er} = \underset{\cdot}{E_t} + \underset{\cdot}{E_s'} + \underset{\cdot}{e_s'}$$

and upon substituting for E_s' and e_s' from (6), (5), (4) and (1) it follows that

$$\underset{\cdot}{E}r = \underset{\cdot}{E}_t \left[1 - \frac{S^2\,(z_s + j\,x_2)}{z_2 + z_s}\right] + \underset{\cdot}{i}_t \left[\frac{j\,S^2\,x_2\,z_s - S^2\,x_2}{z_2 + z_s}\right] \quad (7)$$

Substituting in (7) the relation $\underset{\cdot}{E}_r = \underset{\cdot}{i}_t\,z_2$,

$$\underset{\cdot}{i}_t \left[z_2 - \frac{S^2\,(j\,x_2\,z_s - x_2^2)}{z_2 + z_s}\right] = \underset{\cdot}{E}_t \left[1 - \frac{S^2\,(z_s + j\,x_2)}{z_2 + z_s}\right] \quad (8)$$

The primary current is determined by the condition

$$\underset{\cdot}{i}_1 = \underset{\cdot}{i}_0 - \underset{\cdot}{i}_t = -\underset{\cdot}{E}_t\,y_1 - \underset{\cdot}{i}_t$$

and the primary impressed e.m.f. is given by

$$\underset{\cdot}{E}_1 = -\underset{\cdot}{E}_t + \underset{\cdot}{i}_1\,z_1;$$

hence

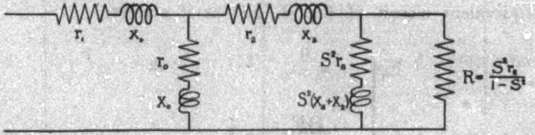

FIG. 5

$$\underset{\cdot}{E}_1 = \underset{\cdot}{i}_1 \left[z_1 + \cfrac{1}{y_1 + \cfrac{1}{z_2 + \cfrac{1}{\cfrac{1}{S^2\,(z_s + j\,x_2)} + \cfrac{1 - S^2}{S^2\,r_2}}}} \right] \quad (9)$$

The expression in the bracket in equation (9) is the equivalent impedance of the motor. Its form shows that the equivalent circuit is as sketched in Fig. 5, in which the exciting circuits are shown as impedances, or as in Fig. 6 where the exciting admittances are drawn.

It is to be noted that the equivalent circuit as here derived differs from the one ordinarily described in that the exciting admittance of the speed field is not constant, but a function of the speed. At standstill ($S = 0$) and at synchronism ($S = 1$)

the circuit of Fig. 6 becomes the same as the commonly accepted diagram, but at all other speeds it differs therefrom. Consequently it is not at once obvious that it is admissible to transfer the exciting circuits to the terminals *a*, *b*, as is usually done.

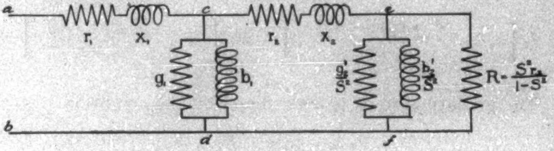

FIG. 6.

Under these circumstances it is of interest to determine the form of the primary current locus, assuming that the so-called "constants" of the motor are unaffected by variations in the load and speed. It is purposed to determine this locus for the equivalent circuit of Fig. 6. just as it stands.

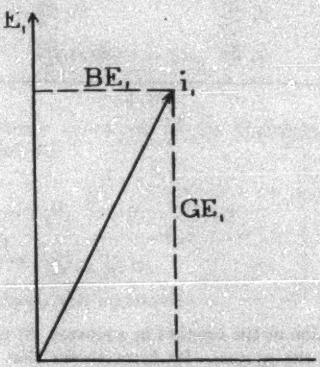

FIG. 7.

It then becomes convenient to transform equation (9) into

$$\underset{\cdot}{i}_1 = \underset{\cdot}{E}_1 (G - j B) \tag{10}$$

where *G* and *B* are, respectively, the equivalent conductance and susceptance of the machine. The impressed e.m.f. E_1 being constant, the equation of the current locus will be given by the relation between G and B and the motor constants.

Referring to Fig. 6 it is clear that between points a and b the conductance is G and the susceptance B; at (c, d) the resistance is $\frac{G}{G^2+B^2} - r_1$ and the reactance is $\frac{B}{G^2+B^2} - x_1$; proceeding in this way through the diagram there results the following table:*

Points	Conductance or Resistance	Susceptance or Reactance	Unit
a, b	G	B	mho
c, d	$\frac{G}{G^2+B^2} - r_1 = \alpha$ (11)	$\frac{B}{G^2+B^2} - x_1 = \beta$ (12)	ohm
c, d	$\frac{\alpha}{\alpha^2+\beta^2} - g_1 = \gamma$ (13)	$\frac{\beta}{\alpha^2+\beta^2} - b_1 = \delta$ (14)	mho
e, f	$\frac{\gamma}{\gamma^2+\delta^2} - r_2 = \varepsilon$ (15)	$\frac{\delta}{\gamma^2+\delta^2} - x_2 = \zeta$ (16)	ohm
e, f	$\frac{\varepsilon}{\varepsilon^2+\zeta^2} = \frac{g_2'}{S^2} + \frac{1-S^2}{S^2\, r_2}$ (17)	$\frac{\zeta}{\varepsilon^2+\zeta^2} = \frac{b'_2}{S^2}$ (18)	mho

Starting first with equation (17) and then with (18), and eliminating successively ε, ζ, γ, δ, α and β, there result

$$\frac{K}{L_1}\left(\frac{g_2'}{S^2} + \frac{1-S^2}{S^2\, r_2}\right)\left[\left(G - \frac{M}{K}\right)^2 + \left(B - \frac{P}{K}\right)^2\right]$$

$$+\left[\left(G - \frac{N_1}{L_1}\right)^2 + \left(B - \frac{Q_1}{L_1}\right)^2 - \frac{1}{4\,L_1^{\,2}}\right] = 0 \qquad (19)$$

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* The Exact Circular Current Locus of the Induction Motor, by K. J Laurell, *Electrical World*, Vol. 52, p. 78.

and

$$\frac{K}{L}\,\frac{b_2'}{S^2}\left[\left(G-\frac{M}{K}\right)^2+\left(B-\frac{P}{K}\right)^2\right]$$

$$+\left[\left(G-\frac{N}{L}\right)^2+\left(B-\frac{Q}{L}\right)^2-\frac{1}{4\,L^2}\right]=0 \qquad (20)$$

Where

$M = A\,r_1+D$

$N = b_1\,r_1+g_1\,x_2+r_1\,x_2\,y_1^2$

$P = A\,x_1+C$

$Q = b_1\,(x_1+x_2)+x_1\,x_2\,y_1^2+\frac{1}{2}$

$K = A\,z_1^2+2\,D\,r_1+2\,C\,x_1+z_2^2$

$L = x_1+x_2+z_1^2\,(b_1+x_2\,y_1^2)+2\,x_2\,(g_1\,r_1+b_1\,x_1)$

$L_1 = r_1+r_2+z_1^2\,(g_1+r_2\,y_1^2)+2\,r_2\,(g_1\,r_1+b_1\,x_1)$

$N_1 = g_1\,(r_1+r_2)+r_1\,r_2\,y_1^2+\frac{1}{2}$

$Q_1 = g_1\,x_1+b_1\,r_2+r_2\,x_1\,y_1^2$

$A = 1+2\,b_1\,x_2+2\,g_1\,r_2+y_1^2\,z_1^2$

$D = r_2+g_1\,z_2^2$

$C = x_2+b_1\,z_2^2$

Eliminating S^2 between (19) and (20) it is found that

$$\left[G-\frac{M\,\frac{b_2'}{r_2}+N\left(g_2'+\frac{1}{r_2}\right)-N_1\,b_2'}{K\,\frac{b_2'}{r_2}+L\left(g_2'+\frac{1}{r_2}\right)-L_1\,b_2'}\right]^2$$

$$+\left[B-\frac{P\,\frac{b_2'}{r_2}+Q\left(g_2'+\frac{1}{r_2}\right)-Q_1\,b_2'}{K\,\frac{b_2'}{r_2}+L\left(g_2'+\frac{1}{r_2}\right)-L_1\,b_2'}\right]^2$$

$$=\frac{b_2'^2+\left(g'_2+\frac{1}{r_2}\right)^2}{4\left[K\,\frac{b_2'}{r_2}+L\left(g_2'+\frac{1}{r_2}\right)-L_1\,b_2'\right]^2} \qquad (21)$$

which is the equation of a circle.

In any well-designed motor terms involving y_1^2 may be neglected; g_2' is likewise negligible with respect to $1/r_2$; but in general it does not appear that any considerable simplification of the final equation (21) is possible several trials having been made using the constants of different motors. It should be noted that the values of g_2' and b_2' are, respectively,

$$g_2' = \frac{r_s}{r_s^2 + (x_s + x_2)^2} \cong g_1$$

$$b_2' = \frac{x_s + x_2}{r_s^2 + (x_s + x_2)^2} \cong b_1$$

III. *Experimental results and conclusions.* In order to check the accuracy of equation (21), several test runs were made on a single-phase motor of standard make. The motor was rated at 5 h.p. at 104 volts and 60 cycles; its constants, determined in the usual way by open-circuit and short-circuit measurements, were found to be:

$r_1 = 0.079$
$r_2 = 0.167$
$x_1 + x_2 = 0.449$
$g_1 = 0.029$
$b_1 = 0.078$

Hence,

$A = 1.045$
$C = 0.231$
$D = 0.169$
$M = 0.252$
$N = 0.013$
$P = 0.466$
$Q = 0.535$
$K = 0.265$
$L = 0.462$
$L_1 = 0.254$
$N_1 = 0.507$
$Q_1 = 0.020$

The abscissa and ordinate of the center of the circle are, respectively,

$$\xi = E_1 \frac{P \dfrac{b_2'}{r_2} + Q\left(g_2' + \dfrac{1}{r_2}\right) - Q_1 b_2'}{K \dfrac{b_2'}{r_2} + L\left(g_2' + \dfrac{1}{r_2}\right) - L_1 b_2'} = 1.19\, E_1$$

$$\eta = E_1 \frac{M \dfrac{b_2'}{r_2} + N\left(g_2' + \dfrac{1}{r_2}\right) - N_1 b_2'}{K \dfrac{b_2'}{r_2} + L\left(g_2' + \dfrac{1}{r_2}\right) - L_1 b_2'} = 0.053\, E_1$$

and the radius is

$$\rho = E_1 \frac{\sqrt{b_2'^2 + \left(g_2' + \frac{1}{r_2}\right)^2}}{2\left[K\frac{b_2'}{r_2} + L\left(g_2' + \frac{1}{r_2}\right) - L_1 b_2'\right]} = 1.04\, E_1$$

The data of a run at a constant impressed electromotive force of 105 volts are plotted in Fig. 8, which shows a satisfactory agreement between the observed and the theoretical current locus. The coördinates of the center of the circle are

ξ = 125 amperes

η = 5.56 amperes,

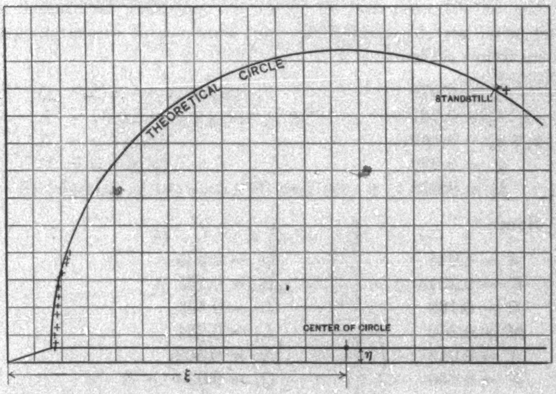

FIG. 8.

and the radius is

ρ = 109 amperes.

It thus appears that statements to the effect that the current locus is a curve of higher order are in error. The locus is a true circle in spite of the complicated nature of the equivalent circuit, and it may be readily determined for any given motor by two simple measurements—primary current and power-factor with the rotor open-circuited, and the impedance voltage and power-factor with rotor blocked and short-circuited.*

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* The writer desires to express his indebtedness to Messrs. W. E. Beatty and I. A. Sims for assistance in obtaining experimental data.

DISCUSSION ON "THE CURRENT LOCUS OF THE SINGLE-PHASE INDUCTION MOTOR." FRONTENAC, N. Y. JUNE 28, 1909

V. Karapetoff: Professor Langsdorf says that he was induced to write this paper because of certain difficulties that he met with in teaching students. I should like to make one slight criticism from a pedagogical point of view. It appears that Professor Langsdorf wanted to get closer to the physical phenomena, and therefore he discarded Ferraris' assumption of two fields revolving in opposite directions. But he introduced another assumption which, while it may be clear to us, is by no means self-evident to the beginner. I refer to the diagram in Fig. 1. He replaces the squirrel-cage rotor by a direct-current armature, or rather by an armature such as is used in some single-phase commutator motors, with two sets of brushes at right angles to each other. These sets of brushes are intended to fix in space two fluxes, the transformer flux and the motor flux, as in the single-phase induction motor. The substitution is hardly justifiable from a pedagogical standpoint. A beginner would not see the equivalence of the two armatures directly. Moreover, this substitution is hardly necessary; for it could just as easily be explained to a beginner that the squirrel-cage rotor, when placed in a motor at rest, would act as the secondary of a transformer; that the same squirrel-cage rotor, if revolved in a constant field, would be equivalent to an apparatus whose field is stationary in space. In this case the flux is in a horizontal direction; that is, along the axis *ff*. For these reasons I think that the substitution of the armature with the commutator for the squirrel-cage rotor is unnecessary. Moreover, it is not quite correct. The squirrel-cage secondary adapts itself electromagnetically to the primary flux, because of the possibility of currents in various bars differing from one another: the equalization is accomplished through the end-rings. In the coil-wound armature, on the contrary, currents in all the coils must necessarily be the same, since the coils are connected in series. Therefore, the student may get a wrong impression, especially with regard to magnetic leakage.

The multistage formula (9) looks complicated because Professor Langsdorf uses reactances and resistances instead of admittances. As I understand it, the only reason is that he wishes to introduce the slip or speed, S. Could not the results be presented in a shape more comprehensive to a student by substituting admittances for impedances? In this case there would not be any stages, but an ordinary addition of terms.

A. S. Langsdorf: In reply to Professor Karapetoff's criticism of the form of Fig. 1, I may say that it has been my practice in class-room work to use both methods suggested by him, but it did not seem necessary to go into such detail in the present paper.

In deriving equation (9) there is little or nothing to be gained in the way of simplicity by using admittances exclusively; the form given in the paper lends itself readily to the determination of Fig. 6, from which the remainder of the work follows directly.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

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MULTISPEED INDUCTION MOTORS

BY H. G. REIST AND H. MAXWELL

The induction motor, as generally used, has a speed which varies slightly with the load but which is usually spoken of as being constant. For work where variable speed is required, a motor with collector rings is used, the speed variation being produced by varying the amount of resistance inserted in the secondary circuit. Such a motor is wasteful of power whenever resistance is used, and the speed varies greatly with the load when much reduction in speed is required.

It sometimes happens that the work is of such a character that two or three speeds will be satisfactory for the operation of the machinery. For such conditions multispeed motors can frequently be used. In these motors the different synchronous speeds are produced by changing the number of poles in the magnetic circuit. Each of these speeds is fixed if no resistance is used in the secondary circuit, so that a change in load will produce only a very slight variation in speed, and the motor will operate efficiently at each speed. With multispeed motors, as with ordinary motors, secondary resistance may be used to vary the speed below each of the synchronous speeds. In this way the complete variation of the speed over a wide range may be obtained more efficiently than with a simple collector-ring motor, but the motor and the control apparatus may be so complicated that the saving of power is not warranted.

A change in the number of poles may be produced in any one of the following ways:

a. By the use of single magnetic and electric circuits, changing the number of poles by re-grouping the coils.

b. By the use of a single magnetic circuit and independent electric circuits.

c. By means of separate magnetic and electric circuits.

The selection and design of the multispeed motor is affected principally by the number of speeds required, the ratio of the desired speeds, and the ratio of the maximum outputs at the different speeds.

a. *Single magnetic and electric circuit*. This type has probably been used more extensively than any other type of multispeed induction motor, due to its economical use of material all of which is active at all speeds. Except in a special case, a disadvantage of this type of motor is the large number of leads which must be brought out of the winding, and the complicated switching apparatus needed for interconnecting them.

For any ratio of two speeds other than 2 : 1, the ordinary three-phase winding requires 33 leads. For a two-phase winding or a three-phase teaser winding, the winding may be arranged with 16 leads. If more than two speeds are desired, the number of leads will be greatly increased and in general will approximate the number made by bringing out the leads of each coil, thus requiring nearly twice as many leads as there are coils in the machine. In this form of motor the same coils are used for the different arrangements of poles, the relative pitch of the winding depending on the number of poles. Since the economy of a winding rapidly decreases when the pitch of its coil is less than one-half, it is disadvantageous to build motors of this type having a greater change of speed than 2 : 1. On account of the large number of leads required, it is not practicable to use this type of winding on the rotors of induction motors, except with a ratio of 2 : 1 speed, with which arrangement only six collector rings are required. With all other speed-ratios the number of collector rings would become prohibitive, so for these motors a squirrel-cage winding is generally used on the secondary.

When the speed-ratio is 2 : 1, this type of motor can be applied advantageously, and a great many have been built and have been in successful operation for several years. A motor wound in this way is practicable for either a wound type of rotor, since it requires only six collector rings, or for a squirrel-cage rotor, which is more generally used.

There are a number of different methods that may be used in connecting the windings of such motors, the selection of the connection in any case depending on the relative maximum outputs required at the two speeds. The connection which has frequently been used where the material is worked to the best advantage, has a half-speed rating of from 60 per cent to 70 per cent of full-speed rating. The following table gives several different connections that may be used, with the approximate relative outputs of the different connections. The third combination shown on this table is the one generally used, as it best suits the average conditions of a load which requires constant torque at the two speeds; that is, when the output of the motor is proportional to the speed.

Speed	Connection	Approximate maximum output
(1) 100	2-Circuit Delta	100
50	Y-delta	11
(2) 100	2-circuit Y	100
50	1 " Y	22
(3) 100	2 " Y	100
50	1 " Delta	66
(4) 100	1 " Delta	100
50	2 " Y	117
(5) 100	1 " Y	100
50	2 " Y	350
(6) 100	Y Delta	100
50	2 Circuit Delta	700

These values are approximate and will vary slightly with the ratio of the reactance to the resistance and also with the ratio of the coil-end to the slot part of the reactance leakage.

From an inspection of the table it will be seen that there is a wide range of choice, from maximum output, a little over 10 per cent for the half-speed connection, to about seven times that of the full-speed connection. These various combinations are often valuable in extraordinary cases to maintain a good power-factor and efficiency at the desired loads. In most of these combinations the material is not worked to equal advantage at both speeds.

b. Motors with a single magnetic circuit and independent electric circuits. This type of multispeed motor has the advantage of using the same magnetic circuit at all speeds, and therefore requires only one stator and rotor structure, the same as an ordinary motor. These motors, having independent windings, have three leads for each speed in the stator for three-phase motors and four for two-phase motors.

The slots in this type of motor are usually made large enough to contain the two or more windings used in making the several windings for the different speeds. It is theoretically possible to obtain a number of synchronous speeds, but it is usually impracticable to use more than two windings. The relative maximum outputs are independent of each other, but to work the magnetic material to advantage it should be approximately proportional to the speed. The motors of this type have to be built large for their output in order to allow space for the increased amount of copper and insulation. The space occupied by insulation becomes excessive on high-voltage motors so that this type is applicable chiefly to low-voltage windings. It is possible in this form of motor to utilize one or more of the windings mentioned in type (*a*), thus increasing the possible number of speeds. Since there are two or more distinct windings, the construction is more complicated and the motors are somewhat more difficult to repair than when only one winding is used.

c. Separate magnetic and electric circuits. The concatenated motor is the only motor of this type in general use. This consists of two motors, the rotors of which are mounted on the same shaft arranged so that the secondary of the first motor is directly connected to the primary of the second motor. The two motors may have the same number of poles, but usually the number of poles is different. The effect produced by the second motor is that of adding to or subtracting its poles from the first motor. It will be seen that if the two motors have a different number of poles, there will be four synchronous speeds, two for the motors independently and two for the combination. If the speed corresponding to the difference in the number of poles is higher than the synchronous speed of the first motor, the set will not accelerate by itself to this speed; and although there might be ways of accelerating to this speed, the switching devices will be complicated so that from a practical standpoint this combination is not generally considered.

By using in concatenation two of the half-speed motors mentioned in class (*a*), the number of speed combinations is very large, and the number of leads and switching of the electric circuits, while complicated, may be warranted in some cases. If, for instance, we take a 4–8 pole and a 6–12-pole motor, we can obtain combinations to give motors having speeds equivalent to every possible number of poles from 4 to 20, except 18.

The ratio of speeds of the two motors is limited by the necessity of changing the poles of each motor, two at a time. A further limitation is the centrifugal stresses in the larger motor at high speeds. If the individual motors have the same synchronous speed and can be run in multiple at the high speed, the ratio of the maximum output of the high speed to the low speed is about 4 : 1. If the load requires this ratio of work with the different speeds, the material in the motor is worked to the best advantage.

The two conditions—of having a load as desired in the foregoing and having speeds with ratio of 2 : 1—rarely exist, so in general the material cannot be economically used in concatenated motors. The ratio of the outputs mentioned is usually unfavorable, since in general the output required at the lower speed is more than one-quarter that required at the higher speed. There are some classes of work, however, such as the driving of blowers, where approximately this load-ratio may exist.

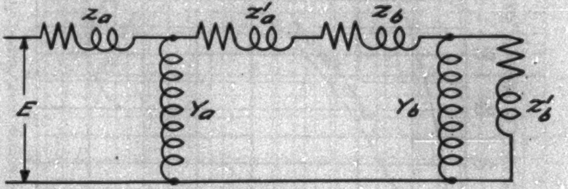

Fig. 1

On account of the large variation in output at the two speeds, the concatenated motors generally use material at the high speed to a very great disadvantage, so that such motors are usually large and expensive for the work to be done. The most favorable condition for the use of the concatenated motor is when the various speeds required are close together. In such a case the two motors would be very different in size and the large motor would be used for the highest speed; for example, if the large motor had 16 poles and the small one had 4, speeds corresponding to 12, 16, and 20 poles could be obtained.

Another disadvantage of the concatenated motor is its low power-factor. This is inherently low, even at the highest speed, owing to the fact that the normal load carried on the individual motors is seldom as large in proportion as the necessary maximum output of these motors in order to obtain sufficient output when the motors are used in combination; in other words, the higher-speed motors will give a poor power-factor because they are underloaded.

To explain the characteristics of the concatenated motors more clearly, attention is called to Fig. 1* which represents circuits equivalently arranged;

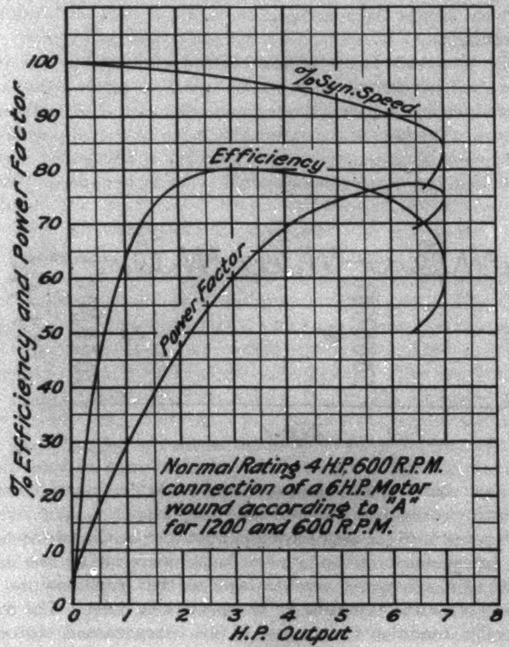

Fig. 2

In this diagram Z_a and Z_b represent the impedance of the primary circuit of the two motors A and B, and Z_a', Z_b' their secondary impedance, while Y_a and Y_b are their exciting admittances. The resistance component of the impedance is here understood to be corrected for each circuit according to the frequency of that circuit, so that all terms are given as their equivalent value for full frequency.

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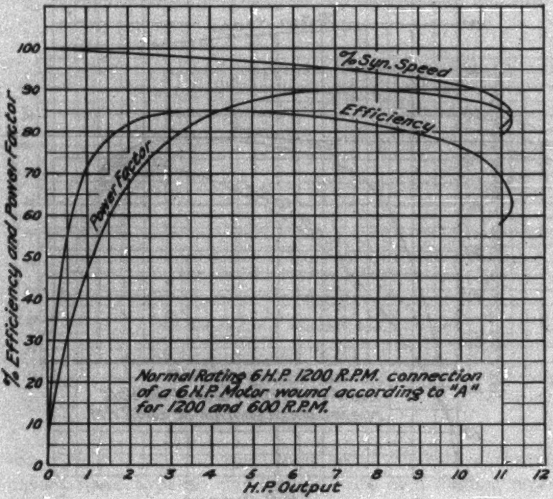
* For explanation of Fig. 1 see E. Arnold, "Die Wechselstromtechnik" Vol. 5, Part 1, Fig. 265.

The load current travels around through Z_a, Z_a', Z_b, Z_b', in series, while the magnetizing circuits Y_a and Y_b are across the line with full voltage impressed upon them, except for the voltage drop in the primary circuit in the winding of A for Y_a, and the additional drop of the secondary of A and the primary of B for Y_b. Since these voltage-drops are small at normal load, we can neglect them and say that the impedances of both motors are added, and, likewise, that the magnetizing currents of the two are added.



Normal Rating 6 H.P. 1200 R.P.M. connection of a 6 H.P. Motor wound according to "A" for 1200 and 600 R.P.M.

Fig. 3

The maximum output of a motor is inversely proportional to its impedance at a given frequency and voltage, so that if the two single motors have equal impedance, the maximum output of the concatenated couple is approximately one-half the maximum output of one motor alone, and its magnetizing current is approximately twice that of one motor—hence its inherent low power-factor in concatenation.

Two curves from actual tests of motors are reproduced to illustrate the points that we have tried to bring out regarding the various characteristics of two of the types of motor mentioned. The curves in Figs. 2 and 3 show the characteristics of a motor of type (*a*) wound for full speed and half speed according to No. 3 connection of the table given. The curves in Fig. 4 show the characteristics of two motors of equal size run in concatenation. Fig. 5 shows the characteristics of one of the motors in Fig. 4 run at the high-speed connection, the other motor being idle. If both motors were run in multiple at the high speed, the output would be twice as great as indicated in Fig. 5.

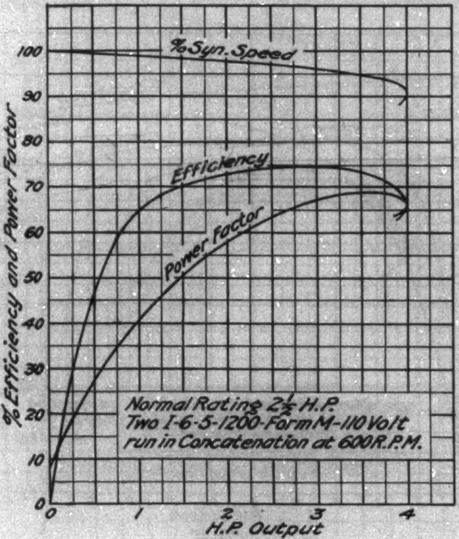


Fig. 4

As a suggestion in the selection of the best type for various conditions, we have drawn up the following conclusions which must, however, be interpreted very broadly, as there are many modifying circumstances.

1. For two speeds having a ratio of 2 : 1, use motor type (*a*).

2. For two speeds having other ratios than 2 : 1, use motor type (*b*), except when the winding and insulation require too much space.

3. When three speeds are required, two having a ratio of 2 : 1, the other being intermediate, type (*b*) may be used with one winding connected as in (*a*).

4. If four speeds are necessary, one speed being one-half of the highest speed, and the lowest speed one-half of the next highest speed, type (*b*) may be used, with each winding such as is used in type (*a*).

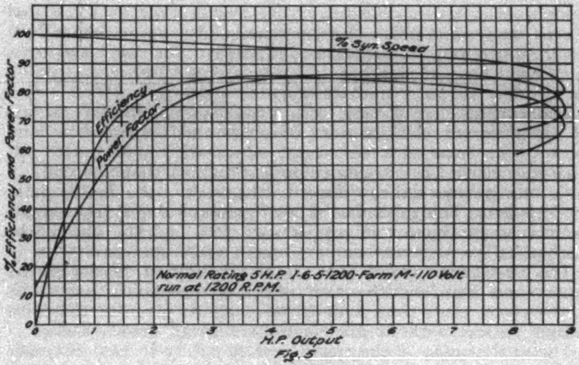


Fig. 5

5. Use type (*c*) concatenated motors, when two or more speeds close together are required.

6. Use concatenated motors when polar windings on the rotor are necessary with more than two speeds, or if the two speeds differ from 2 : 1.

7. Use concatenated motors for high-voltage machines except when type (*a*) can be used.

DISCUSSION ON "MULTISPEED INDUCTION MOTORS." FRONTENAC, N. Y., JUNE 28, 1909

H. C. Specht: It is well known that the induction motor is the simplest motor to build and operate. It can be used with advantage for a variety of purposes, especially for constant-speed service. Where variable speeds are required, however, the induction motor is put at a disadvantage by the direct-current motor.

A great many methods for varying the speed of the induction motor have been employed. Some of these methods are discussed by Messrs. Reist and Maxwell, but treat chiefly of motors in concatenation and with multispeed apparatus consisting of a single motor. For a two-speed motor consisting of a single winding, and with a speed ratio other than 2:1, the authors say that 33 leads are required for a three-phase winding. It would be of interest to know whether this applies to any speed ratio other than 2:1 and to any number of poles, or what particular combination of two-speed connections the authors had in mind. For various schemes of connections the number of leads is generally dependent on the number of poles and the type of winding.

The authors give a table of approximate maximum outputs for the different combinations of series and multiple, star and delta connections of a two-speed motor with a ratio of 2:1. I assume from the maximum output figures that the coils of the windings have a throw closer to the pitch of the double number of poles. This table would be of greater value if the current, the necessary amount of copper and iron, and the size of the mechanical parts were compared with some standard.

The maximum output depends on the limited density in the copper and iron, and the stresses in the mechanical parts. It is, therefore, clear that some of the outputs given in the table cannot be met without increasing or wasting some material.

The authors say, if the speed corresponding to the difference in the number of poles is higher than the synchronous speed of the first motor, the set will not accelerate by itself to this speed. This statement would be correct if the first motor, which has the greater number of poles, is connected to the line. If the synchronous speed of the second motor is higher than that of the differential concatenation, then the second motor, instead of the first motor, may be connected to the line. In the case where neither of the two motors has a higher synchronous speed than that of the differential concatenation, the speed for the latter cannot be obtained without auxiliary means.

In regard to a cascade set consisting of two two-speed motors each one having pole ratio of 2:1; I know that 12 different speeds can be obtained. For example, the first motor having 10 and 20 poles and the second motor 2 and 4 poles, speeds corresponding to the following number of poles can be obtained: 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, and 24. In case only one of the two motors is a two-speed motor, the maximum number of speeds is 7.

It may be well to mention, however, that the different speed combinations are not practicable in every case. Furthermore, sometimes it might not be possible to obtain the exact speeds for every one of the different connections. In such cases the two motors may be interconnected mechanically by means of gears, chains, etc. having a speed-ratio which will give the desired speeds. It is clear, then, that practically any possible combination of speeds can be obtained with a cascade set; whereas with multispeed motors consisting of a single motor, such variations in the number of speeds cannot be obtained.

The authors say that the number of speeds obtained by a cascade set is limited by the centrifugal stresses in the larger motor. This limitation is, however, much less than on a single multispeed motor for the same speeds. The individual motors of a cascade set can be designed so as to have greater width and smaller diameter, thus keeping the peripheral speed lower than would be the case with a single motor.

The electrical performances of a cascade set depend entirely on the design of the individual motors. The curves given by the writers have reference to a particular design only.

There is no doubt that the motors for concatenation are very simple and safe in regard to control and operation. Even though the cost of a cascade set is rather high, it can be recommended in various cases, especially where simplicity and safety of control and operation are of great importance. The application of one or the other method of the various multispeed motors depends on so many conditions that a general rule as to which method should be used can hardly be given.

A. M. Dudley: I would like to call attention to another method that has been used for getting multispeeds. Quite a little has been done with it in England. I refer to the so-called method of internal concatenation. This is accomplished by winding the stator and also the rotor of a motor of normal mechanical structure for two sets of poles. If the line current is led into one of the stator windings, the other being short-circuited, and the two rotor windings are connected in series, the motor will run with a synchronous speed corresponding to the sum of the two pole numbers for which the motor is wound. Resistance may then be inserted in the remaining stator winding for varying the speed, as in the case of a normal wound secondary motor. For example, if the stator is wound for 4 and 6 poles, and the rotor also, it is possible by means of such a connection, using a single magnetic and also a single electric circuit, to have a speed corresponding to 10 poles.*

Charles P. Steinmetz: There are two methods of getting different speeds from the induction motor. One is by changing the number of poles, the other by concatenation or cascade connection. Anyone who has designed an induction motor realizes that the difficulty in getting good motor constants is to give sufficient peripheral speed without increasing excessively the size of the motor. A large pitch per pole, that is, many ampere-turns per pole, is necessary to get a reasonable exciting current and reasonable leakage flux. Changing the number of poles; for instance, doubling them to get half-speed, reduces the pole-pitch one-half. The motor constants are thereby made twice as bad. That is the disadvantage of changing the number of poles. It means that this type of multispeed motor is more difficult to design for low-speed operation. A motor well designed for the low speed produces an excellent machine for high-speed operation; but in any case the motor has to be more carefully designed than would be demanded by a motor intended merely for high-speed service. Unfortunately, concatenation does not overcome this difficulty; for in this case the second motor is fed from the first motor. While the motor always keeps the same number of poles, and thereby the full pole-pitch, the first motor carries not only its own, but also the second motor's exciting current; and its leakage reactance is the sum of the leakage reactances of both motors, as the second motor is an inductive load on the secondary of the first motor. Thus concatenation doubles the exciting current and the self-inductive impedance, making the constants of the motor twice as poor, just as is the case when doubling the number of poles in one motor. In short, the electrical characteristics of the concatenated couple of motors are the same as the electrical characteristics of one motor with a changeable number of poles.

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* See article by Dunn, *Journal of the Institution of Electrical Engineers*, September, 1907.

That brings us to the question of the relative characteristics of the two types of motors. I have been interested in the subject for many years, but have been forced to the conclusion that, in general nothing is gained by concatenation over the method of changing the number of poles in a single motor; but something is lost by having two structures instead of a single structure. Concatenation is therefore applicable only to special purposes, as in the case of railway motors. For general stationary work, the motor with a changeable number of poles is generally preferable.

H. C. Specht: In regard to the statement made by Dr. Steinmetz that the rotor of the motors in a cascade set has to be greater in diameter, thus necessitating a higher peripheral speed; this is a question of design. If the motors of a cascade set are properly designed, the diameters can be kept smaller than on single multispeed motors. Consider, for example, a cascade set of which one motor has 12 poles and the other motor 4 poles, and speeds corresponding to 12 and 16 poles are required. In this case the motor with the 12 poles would be designed with a leakage, almost equal to that of an ordinary single-speed motor. Then the motor with 4 poles would have to be designed with very small leakage, so that the total leakage of the set would be very little increased over that of the 12-pole motor. With such a design it is clear that the 12-pole as well as the 4-pole motor could be designed with a smaller diameter than a two-speed motor having a 12 and 16-pole winding.

Charles P. Steinmetz: It is entirely correct that a 4-pole motor can be designed with much smaller leakage flux than a 16-pole motor; and concatenated to the latter, the former would be less liable to spoil the constants of the couple than if it also had 16 poles. But the same applies to changing the number of poles: changing from 16 to 20 poles would spoil the motor constants less than doubling the number of poles. The two methods, concatenating two motors, or changing the number of poles of one motor, still give essentially the same change of motor constants with changes of speed.

E. F. Alexanderson (by letter): One of the speakers referred to the method of speed variation by means of internal concatenation, and to an article published on this subject in 1907. I designed a motor of this kind in 1904. This experimental machine was built with the object of testing the internal concatenation as well as the connection of the same machine as a frequency-changer from 25 to 60 cycles. At the same time tests were obtained on a motor with two sets of windings; in other words, a motor which combined a four-pole and a six-pole winding on the same structure.

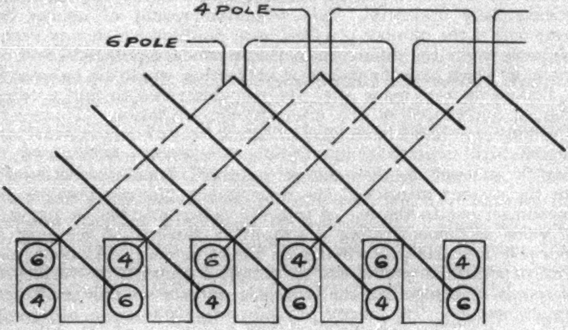

FIG. 1.

The field as well as the armature of this motor was made from the windings of a standard six-pole motor without changing anything but the connection of the coils. To my knowledge this was the first machine built with a double set of windings without introducing any special feature in the arrangement of the coils. Fig. 1 shows that each slot contains one member of the six-pole and one member of the four-pole winding, and that the two windings alternate in the upper and the lower positions of the slot. The test confirmed the theory and demonstrated that the two windings were electrically independent and operated in the same way as if wound on separate cores connected to the same shaft. The machine could therefore be used as a concatenated set of motors or as a frequency-changer, in accordance with well-known methods. In the case of internal concatenation the collector rings were not used.

An interesting feature which was specially studied was the magnetic combination of the two fluxes. It had been foreseen in the design of the machine that two fluxes would combine in a resulting flux with an unbalanced distribution so as to cause a one-sided attraction of the armature, and a special reinforcement had been provided in the armature in order to avoid mechanical resonance. The test demonstrated, however, that no reinforcement could be applied to the shafts and bearings that would reduce the vibration sufficiently to make the machine commercially operative. This objection would of course be overcome if the number of poles were doubled, or in any combination where the difference in the number of poles was four or more, in which case the magnetic attraction would be balanced.

Endeavors were made after the test described to find a commercial application of the internal concatenation. However, it is difficult to find a justified application for ordinary concatenation and still more so for internal concatenation where a limitation is imposed on the relative number of poles. Although for the reasons mentioned the experiment did not give much encouragement to the use of internal concatenation, it proved of value as demonstrating a simplified method of winding a four-pole and a six-pole winding on the same core. At the same time experiments were made to obtain a continuous variation of speeds by controlling the four-pole and the six-pole windings simultaneously. The scheme proved perfectly feasible, although of course it gave a low efficiency. The most practical combination, after all, which was tried was simply a squirrel-cage rotor and a switch for changing the four-pole winding into an eight-pole by the well-known Dahlander-Lindstrom connection. In this way a good three-speed motor was produced with four, six, and eight poles.

A. E. Averett: In the concatenated motor the speed reduces somewhat in this way: with the collector-ring single-speed motor the reduction in speed is accomplished by reduction in efficiency, the power-factor remaining constant. In the concatenated motor the efficiency will remain approximately constant, but the power-factor goes down as the speed is decreased. The power-factor on the line is therefore high with secondary resistance, as against a low power-factor wheret he speed reduction is gained by concatenation.

H. G. Reist: The 33 leads mentioned are for a motor of the first class and will include any ratio of speed if the windings are Y-connected.

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OUTPUT AND REGULATION IN LONG-DISTANCE LINES*

BY PERCY H. THOMAS

The limitations of the power transmission line as to distance, power, and voltage, and its characteristics as to voltage-variation and energy-loss, have always excited a great deal of interest in the electrical art. The subject has been treated by a number of prominent engineers in its various phases, notable among these being Scott, Perrine, Steinmetz, and Mershon. These men and others have done pioneer work and have outlined the general limiting conditions of transmission. There are some of the relations and peculiarities of the long line, however, that are of importance and interest which have not, to the writer's knowledge, been clearly presented before electrical engineers. It is the object of the present paper to discuss some of these features, more especially the line-output, regulation or voltage-variation, and the line energy-loss.

In view of the uniform distribution of the resistance, inductance, and capacity in a transmission line, a proper study of the long line cannot be made without a suitable formula or equation for calculating the true effect of such a line on the electric current transmitted. As far as the author is aware, no such formula having a form sufficiently simple for convenient use and applicable to the ordinary transmission calculation has been offered. In the paper entitled " Calculation of the High-Tension Line," such a formula is derived, and is recommended for numerical computations in practical work where accurate results are desired.

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* It is intended that this paper shall be considered in connection with a companion paper presented at the same time and entitled, "Calculation of the High-Tension Line."

In the analysis of the effects of the transmission of energy through the line which is to be given, reliance has been placed upon the "wave" formula, as it is here called, though check calculations have frequently been made from an approximate formula based on the usual assumption in transmission calculations—that the capacity of the lines is concentrated at the ends. This second formula, while based on approximate assumptions, is of very convenient form. It is called the "split capacity" formula, and is found in the companion paper.

With this introduction, the basis of the following discussion will be clear. While the principles stated apply in the main to lines of all sorts, they are of numerical importance and of special interest chiefly in the longer and relatively high power lines. The determination of their bearing on practical transmission must await the further development of the art.

Electrical action in the line. The critical electrical feature of a transmission system is the action of the line itself. In the passing of energy over a line there is, first, the loss of energy, in practical overhead work represented only by the resistance losses. But with power passing over a line at high voltage, a certain amount of leading energy flows to charge the line capacity. This energy in its travel causes a tendency for the potential to rise along the line in the direction of the flow of the leading energy. Similarly there flows to the line a quantity of lagging energy, in virtue of the inductance of the line and the flow of current therein. This lagging energy tends to cause a drop of potential in the line in the direction of its flow. The resultant effect is the difference of the leading and lagging energy-flow, superimposed, of course, upon the true power transmitted and the resistance-drop.

This use of the terms "leading energy" and "lagging energy" is a little unusual; it is adopted only in the absence of a more suitable term for this situation. By "leading energy" is meant that flow of energy which is absorbed by the line capacity on rising voltage and is returned on falling voltage. By "lagging energy", is meant that energy which is absorbed by the line inductance on rising current and returned on falling current.

When the lagging energy predominates cver the leading energy, the tendency is for a drop in potential along the line in the direction of the lagging flow—the well-known inductive drop, which is combined with the ohmic drop.

When the leading energy predominates there is a tendency for a rise of potential in the direction of the leading energy-flow, which must be combined with the ohmic drop as before. The rise of potential effect of the leading energy will be opposed to the ohmic drop when the transmission of power and the flow of leading energy are in the same direction. If they flow in opposite directions in the line their effects will, however, be in the same sense.

Now consider the case when the leading and the lagging energies are equal and when they are opposite in phase; that is, when the load power-factor = 1. In this case there will evidently be no appearance in the line or demand on the generator for either lagging or leading energy, and no tendency either for a rise or a drop of voltage therefrom, and the ohmic drop is the only loss of voltage. This condition will be actually realized in practice if the leading and lagging energies of the line are equal and with a load of unity power-factor. If, however, the load current has a lag or a lead, the leading and lagging energies, while they may be equal, will not be opposite in phase and will not neutralize each other. The rather remarkable conclusion follows—that in this case of complete neutralization the loss of voltage is only the ohmic drop and is independent of frequency and is of the same value as with direct current. Thus if this condition can be realized, and there enters no secondary effect, there will be no further economy in direct-current transmission as far as energy-loss or voltage line-drop is concerned, the same effective line voltage being used. But the difficulty is that this condition of equality of the leading and the lagging energy in the line is usually not met with in practical transmissions of relatively short length, and often cannot be economically obtained.

The unfortunate condition exists that the leading energy, being the condenser energy, is practically constant, whatever the load on the line, since it depends only on the voltage of the line. On the other hand, the lagging energy depends only on the actual amount of power or current being transmitted, since it varies as the square of the line current. Thus with half load or no load, a line that was balanced for full load would have a large excess leading energy flow.

Suppose a line to be laid out so that there is an equality between the leading and the lagging energy at full load. At full load the line-drop in the direction of the power-flow will be the ohmic drop; but at half load the leading energy-flow will greatly predominate, and the actual line-drop in the original direction will be the ohmic drop less the effect of the excess leading energy in tending to produce a rising voltage in this direction. This assumes the leading energy to be supplied in the same direction as the power. Just what the resultant would be depends on the particular constants of the case. Now, when the load becomes zero, the line-drop will become a rise to the extent of the ability of the leading energy to bring about this result, since the ohmic drop will then be zero. Thus the range of delivered voltage from no load to full load will be the sum of the ohmic drop at full load and the leading energy rise at no load, which will in long lines be a very material amount.

In the case assumed suppose, however, that the power is transmitted in one direction while the leading energy is supplied from the other in any suitable manner. Then the full-load drop is the ohmic drop, as before; the no-load drop will be of the same numerical magnitude as before, but in the opposite direction. That is, the no-load drop will tend to make the end from which the true power is furnished the higher in voltage. Now, this is the same direction of potential-slope as the ohmic drop caused in the full-load condition of the line; thus the no-load and full-load cases show the same line voltages at both ends, provided, of course, the ohmic drop is equal numerically to the leading energy-rise at no load.

This relation of full-load and no-load drop may be often quite well approximated. When it is attained, the voltage variation of the line ceases to be a limiting feature of the transmission, and the amount of power that can be carried on a single line depends only on the amount of copper used. The effect of frequency, as already stated, is almost eliminated, within reasonable limits.

The practical problem, then, is to find some satisfactory way by which to realize the ideal adjustment of leading and lagging line energy, and also the approximate equality of the leading rise of voltage at no load with the ohmic drop of voltage at full load in any particular case.

It should be carefully borne in mind that the leading and lagging energy and energy-loss so far discussed are wholly confined to the line and have no necessary relation to the leading or lagging current in the load.

The factors by which the relative values of the leading and the lagging energy of the line are controlled are the line voltage, the actual load or current, and the ratio of the line inductance and capacity per unit length. The energy taken by the capacity of the line varies as the square of the line voltage, so that this factor is of extreme importance. The lagging energy of the load varies as the square of the current, as has already been mentioned. Neutralization of the leading and lagging line energies can be obtained only when the power-factor of the load current is unity, for only then are the leading and lagging energies opposite in phase.

The current of the line, of course, decreases directly with the increase of line voltage chosen, if the power transmitted be kept constant.

The energy flowing to the capacity of the line per unit length is proportional to $p\,C\,V^2$, where $p\,C$ is the capacity susceptance and V the voltage. The lagging energy will be proportional to $p\,L\,I^2$, where $p\,L$ is the inductive ohms and I the current. If these are equal then $\frac{V}{I} = \sqrt{\frac{L}{C}}$, which is the condition of balanced out-of-phase energy. It is clear that this can be reached for any line and voltage by properly choosing the current, and for any current by properly choosing the voltage. It is also clear that the condition is independent of frequency.

Equation (34) of the companion paper gives the line voltage equation when $R = 0$. Here if the current or voltage is chosen to fulfil the above condition, the generator voltage $= S \sin (p\,t + \theta + x\sqrt{p^2\,C\,L})$, showing that the voltage of the line is constant, as it should be. The resistance is chosen as zero, as otherwise the change of voltage along the line will destroy the exact balance of the leading and the lagging energy.

Thus as the net result, the ratio of the leading to the lagging energy varies as the fourth power of the voltage when the power transmitted remains the same. The capacity of the line can be increased by adding condensers in parallel across the line at regular and sufficiently frequent intervals; the inductance can similarly be increased by the addition of choke-coils in the same manner. But these expedients have never found much favor. As the power and voltage are often fixed by other considerations, some other method of altering this ratio than by change of power or voltage would be desirable.

The following method is suggested for consideration in favorable cases. The several line conductors may be divided into two, three, or more wires, which are separated somewhat from one another but mounted on the same insulator or adjacent insulators, the current dividing between them. The effect of this arrangement will be to increase the line capacity and to decrease the line inductance, both of which changes tend to alter the ratio of capacity to inductance in the same direction. With large power and long-distance lines, this increase of ratio is found in many cases to be in a favorable direction. This plan will be further discussed at a later point of this paper. Formulas for numerical calculations will be found in the companion paper.

It should be said that in this matter of adjustment of the leading and lagging line energies, a change of frequency is of no avail, since both elements, capacity and inductance, are affected in the same manner. Furthermore, while a certain voltage may be most favorable in some particular case for balancing the line effects and reducing the line-drop to the ohmic equivalent, it does not necessarily follow that this voltage will give the best transmission condition; for the advantage of a higher voltage may easily more than offset the favorable adjustment of the leading and lagging energy of the line. Furthermore, the most favorable line conditions will not always be the most favorable for other parts of the system, and any complete design will be a compromise, as usual.

Instead of feeding leading and lagging current from one end of the line or the other, it may be fed from both. In this case the result will be the resultant of the various tendencies already explained.

It is clear that the end from which the leading or lagging current is fed determines the direction in which the rise or fall of potential will be found. In other words, the same current that is leading, considering the direction from power house to the receiving end, will be lagging if taken in the other direction. A leading current fed into the line from the generator end tends to cause a higher potential at the receiving end, while the same current fed from the receiving end tends to cause a higher potential at the power-house end.

If the leading current be fed equally from both ends, the potential will tend to rise toward the middle and fall toward both ends of the line. Similarly with lagging currents; if the currents fed from the two ends are not equal, the point of maximum potential will be thrown in one direction or the other, toward the end into which the smaller current flows. Thus in the control of the potential of a line, it may be advantageous to supply the leading current from the receiving end or from both ends, as will be pointed out later.

If the so-called synchronous form of generator be used there would be no difficulty in supplying the necessary amount of power and lagging or leading current to the line, as may be required in any case, but if either lagging or leading energy be demanded at the same time as useful power, the capacity of the generator must be greater in inverse proportion to the power-factor. This is well known.

If the lagging or leading energy be supplied from the receiving end of the line, it may be supplied either by additional generators at this point or by synchronous motors or converters. One disadvantage of this arrangement is the difficulty of making the two generators at the opposite ends of the line divide the line current between them in the desired ratio or of making the generator or the synchronous motor or converter at the receiving end supply all the leading current to the line to the exclusion of the power generator. Of course there would be no difficulty in making the power-house generator supply all the useful power, as this function is determined by the governor of the prime mover.

Where it is desired to supply the leading current to the line from the receiving end, the expedient is suggested of using non-synchronous generators at the power-house end, and synchronous motors or auxiliary generators at the receiving end. In this case the non-synchronous machines, while generating the amount of power for which their governors may be set, will take only a certain definite amount of magnetizing current; that is, current suitable to supply leading energy to the line from the power-house end. The no-load leading current, except for the magnetizing current of the non-synchronous machines, will then be supplied from the synchronous machines at the receiving end, as is desired. The use of synchronous motors driven from non-synchronous generators has been fully discussed by Waters in the Institute TRANSACTIONS.* This use of non-synchronous machines will be again discussed later in this paper.

But the load as well as the line must be considered. Unfortunately, the load has its own particular characteristics, independently of the other parts of the system. Its power-factor is not determined by the line current or the line conditions. It must take a certain current, usually lagging, and its requirements will vary as the load changes. Thus other conditions must be suited to the load conditions. But the line, when adjusted for best internal conditions of balanced leading and lagging energy, will deliver current without lag to the load, which is not usually suitable. In case the line conditions are not to be wholly sacrificed to the load condition—this is usually the case in most transmissions of moderate size—it is necessary to supply the load lagging current by synchronous apparatus, either motors or generators. Such an arrangement is perfectly feasible, though not often used at the present time. In case such synchronous apparatus at the load end has been already determined upon to supply leading current to the line, as already explained, these same machines may serve both functions. It is to be noticed that the lagging current of the load and the leading energy supplied by the synchronous machines into the line from the receiving end tend to neutralize each other; and that if a leading current enters the line from the receiving end equal to the lagging current of the load these will balance each other and there will be no current taken from the synchronous machine.

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* A.I.E.E. TRANS. Vol. XXVII, 1908, p. 157.

A compromise may be effected between the best line condition, requiring the delivery from the line of current at unity power-factor and the best condition from the point of view of the synchronous machine, in which the load lagging current at full load should be supplied wholly from the leading line current.

In the main the electrical action of the line has now been briefly outlined. The most notable features are:

1. That by properly balancing the leading or capacity energy and the lagging or inductive energy in the *line itself*, the full-load transmission will be as though the line had only ohmic resistance.

2. That a reasonable constancy of voltage conditions on the line *for all loads* may be obtained by supplying the leading energy in the condition when the load is off or light, partly or wholly from the receiving end.

In actual cases of transmission it is usually found that the lagging component so far overshadows the leading component as to render the former the dominating feature. In this case the only expedient for controlling line-drop would seem to be to raise the voltage or to limit the maximum load. It will be possible, however, in such cases to apply the suggestion made above—to divide the conductor to reduce the line inductance and increase its capacity. In the case of large excess lagging current, the loss of capacity and good regulation in the generators due to the lagging component of the load added to that of the line is well understood. The lagging component of the load can be balanced by synchronous machines at the load end, but this adds too much complication for most plants, or at least seems to be so considered. Where such synchronous machines are not used at the receiving end, a large line capacity current may be desirable to balance the load lagging current.

But it is not the purpose of the present discussion to consider the smaller plants as distinguished from the large long-distance systems in which it is feasible to balance the leading and lagging line energy.

There is a remarkable effectiveness of the arrangements here suggested in rendering practicable, electrically speaking, the transmission of large amounts of power in a single line for long distances with an acceptable voltage regulation. This can best be shown by means of a few actual examples. The first case assumed (case *a* Table A) has been taken to represent the transmission distance of the well-known Victoria Falls transmission, but all attempts to parallel the other commercial or engineering conditions of this project have been carefully avoided.

The transmission is taken as having 700 miles of three conductors spaced 12 ft. apart and each having three times the section of No. 0000 wire. The frequency is taken as 25 cycles. Assume at the start that the power to be delivered at full load is 40,000 kw. at 150,000 volts and with a load power-factor of 0.85. Assuming that synchronous machines at the receiving end supply all of the load lagging current except enough to charge 300 miles of the line—giving a line power-factor of 0.918 at the receiving end—the drop in voltage will be 12.1 per cent and the generator power-factor will be 0.96, leading. The true energy-loss in the line will be 10.4 per cent., giving what seems to be at first not an unfavorable condition. The effect of throwing off the load (case *b* Table A), however, is to cause a rise in voltage of about 21 per cent, above generator voltage assuming that the synchronous machines at the load end supply no leading energy in the no-load condition or that they have dropped off the line. This gives too great a range of voltage at the receiving end for satisfactory direct operation,

TABLE A.
ILLUSTRATIVE LINE ADJUSTMENTS WITH CALCULATIONS.

	Distance in miles	Size of conductors	Spacing of conductors in feet	Transmitted power, three phase	Line voltage delivered	Line current load end, "–" means leading 1 ϕ – equivalent	Frequency	Line power-factor, load end	Voltage drop in % of generation voltage	Line energy loss in % gen. power	Line power-factor generator end "–" means leading	Line current generator end, "–" means leading 1 ϕ – equivalent	$\frac{\phi x}{v}\left(\frac{360}{2\pi}\right)$
a	700	3 #0000	12	40,000	150,000	145.3	25	0.918	12.1	10.4	–0.963	134.8	34° 48′
b	"	"	"	0	"	0	"	—	–21.4	—	—	—	"
c	"	"	"	60,000	"	200	"	1.00	11.5	13.8	–0.994	206.8	"
d	"	"	"	0	"	–63.8	"	0	–.2	—	—	—	"
e	"	"	"	60,000	"	202	60	0.99	7.2	13.2	–0.974	219.7	83° 6′
f	"	"	"	67,500	"	225	25	1.00	15.7	15.3	1.000	224	34° 48′
g	"	"	D* "	60,000	"	235	25	0.85	15.7	11.7	–0.96	199	35° 6′
h	"	(3¼) × #0000	D* "	75,000	"	278	"	0.90	19.6	13.7	–0.988	237†	"
i	"	"	D* "	50,000	"	231.6	"	0.72	17.5	11.5	–0.962	161.4‡	"
j	"	"	D* "	0	"	–175	"	0	10.4	2% 75,000 kw	–0.09	–53.3	"
k	300	3 #0000	"	60,000	"	235	"	0.85	17.1	7.8	0.876	205	Sp't Cap.
l	"	"	D* "	"	"	"	"	"	11.4	7.3	0.971	196.6	Sp't Cap.
m	"	$(\frac{2}{3})^2$ × #0000	10.5	12,000	100,000	75	60	0.80	6.23	4.46	0.873	67.5	35° 36′
n	"	"	"	20,000	"	125	"	"	20.2	7.00	0.998	86.1	"
o	"	"	D* "	50,000	"	250	"	1.00	14.5	14.8	1.000	250.7	35° 48′

D* means divided conductor, each line wire divided into three separate conductors spaced 18″ apart. Inductance reduced to from 0.60 to 0.59 of normal.
† Leading component of line current at generator end = 36.5.
‡ Leading component of line current at generator end = 44.2, compare 53.3 amperes in case *j*.

but probably would be satisfactory for the regeneration of the power.

In this case it is evident that the leading energy in the line greatly overbalances the lagging energy in the line taken as a whole, but that at the load end the lagging component of the *load* causes a predominance of lagging at this end of the line, which is gradually overcome by the leading excess in the line until at the generator the leading energy predominates. This is in a way a favorable combination, for the load might easily be supplied with lagging current without the intervention of synchronous machines at the load, and yet the general excess of leading energy in the line tends to limit the line drop. The weak point of this arrangement is the rise in line voltage from generator to load on no load or light load, and the increased line energy-loss.

To balance the line leading and lagging energy components at full load, we may increase the total powert ransmitted, making it 60,000 kw. delivered (case *c* Table A). In this case to obtain unity power-factor at the load it may be assumed that there are synchronous generators to carry the load lagging current, as distinguished from the lagging line energy. The line drop will then be 11.5 per cent and the generator power-factor 0.994 leading, showing that the line leading and lagging energies are about equal. In this case the line current is approximately the same all the way through the circuit, and the line energy-loss calculated by the wave formula is 13.8 per cent, almost exactly the product of the resistance and the square of the delivered current, as it must be. The line drop is a little less than the product of the resistance and load current in this full-load condition, on account of the slight excess of the leading energy in the line.

Now if it be assumed that the leading current for the no-load condition be supplied from the load end, then the rise in voltage backward along the line from the load end to the generator end will be 21 per cent (see case *b* Table A). This is the same thing as a drop of the same amount in the direction of the power transmission, the net change in line voltage from full load to no load, and is only 10.5 per cent and this occurs at the power house, provided the voltage of the synchronous apparatus at the load end, which does the magnetizing, is kept constant by some regulator or other means. Thus this condition is a highly satisfactory one for the transmission, provided no indirect disadvantages appear.

If, on the other hand, enough charging current—about 64 amperes—be fed from the receiving end to charge about 300 miles of line, the rest being supplied from the power-house end, the no-load voltage at the power-house end will be 0.2 per cent lower than at the receiving end, showing the effect of feeding leading current from both ends (see case *d* Table A). The potential at the middle of the line, however, will be somewhat higher than at either end.

In the case just assumed the synchronous machines must carry the whole lagging component of the load at full load and leading energy for the line at no load.

But it is possible to improve the practical conditions a little by allowing a certain portion of the load lagging current to be carried by the line capacity, as the leading and lagging components are at right angles to the power component and produce little effect in the line as long as they are relatively small. Line charging current flowing from the line out to the load is there actually seen as lagging current. As far as carrying the lagging component of the load is concerned, the work to be done by the synchronous machines will be reduced by this expedient, thus permitting a larger power output for a peak load, though the no-load condition will be unchanged.

To accomplish this result, it will be necessary to increase the line capacity energy or to decrease the load. If the former alternative be chosen and the expedient suggested above of dividing the line conductors be used, assuming three conductors, each equal to one No. 0000 wire with the same average spacing but separated individually 18 in., the line inductance and capacity will each be altered in approximately the ratio 0.6. The line conditions will then be such as to give a drop of 15.7 per cent (see case *g*, Table A) taking the power-factor as 0.85 at the load at full load. This will give a power-factor at the generator of 0.96 leading. The drop has been thus increased as the lagging excess at the receiving end of the line dominates the leading excess at the power-house end. Here as far as the line itself is concerned, the leading energy far exceeds the lagging energy, with the consequent wide variation of current and power-factor through the length of the line. The lagging load component of the load entering the line at the load end is sufficient to dominate the line near this point, though the excess of leading energy in the line soon overpowers the lagging and leaves the generator current leading by a considerable factor.

These line conditions, while not the best for the line itself—the drop has increased to 15.7 per cent—is in some ways better than in case *c*, on the whole, as there is no call ont he synchronous apparatus at the load end at the full-load condition, and this apparatus is available as an auxiliary for supplementary power to carry peak loads. But it is evident that the leading component of the line is unnecessarily large, and a larger amount of power would more nearly balance the leading and lagging energies. Thus, assuming that the power be increased to 75,000 kw. and the power-factor at the load end be made 0.90 and that at the same time the section of the conductor be increased 25 per cent to keep down the true line energy loss, then the line-drop will be 19.6 per cent (see case *h*, Table A) and the generator power-factor will be 0.988 leading. The line loss is then reduced to 13.7 per cent. This is a favorable condition, for the energy loss is low, the synchronous apparatus is called on only for a relatively small amount of lagging current at full load, assuming that the *load* power-factor is as before 0.85, and at no load the synchronous apparatus is free to supply the leading energy to the line. On no load the rise in voltage toward the generator will be 10.4 per cent (see case *j*, table I), assuming 175 amperes charging current at the load end, which gives a net change at the power house of some 9 per cent, which is entirely satisfactory. This assumes constant voltage to be maintained at the load end by the synchronous machines.

Thus it is seen that by the principles here expounded, it was possible practically to double the output of this line over that obtained by the ordinary method of operation. This double output was obtained with a very much more satisfactory voltage regulation, and with a true energy loss that could be reduced to any desired value by the mere addition of copper.

It is interesting to note that the cost of copper per kilowatt, in the line with 75000 kw. transmitted and copper at 16c. is about $56, by no means a prohibitive value.

Similar examples might be worked out for higher frequencies, where these are desired, and though the service will be much more sensitive to the accuracy of proportioning, there is no theoretical reason why nearly as good regulation should not be gotten with 60 cycles as with 25.

Case *c*, Table A, above, taken for 60 cycles would give the results shown in case *e*, Table A. Here a slightly lower load power-factor has been chosen, since the leading energy is slightly in excess. The results are very nearly the same for both frequencies, the drop being less with 60 cycles on account of the greater excess of leading current at the power house.

To show a more exact balance between the leading and lagging energy than is shown in case *c*, case *f* has been calculated for the same line with a somewhat larger load, 67,500 kw. The power-factor is here found to be unity at both ends of the line, the current the same within less than one half per cent, and the energy-loss nearly equal to the drop in per cent. The drop calculated as the product of the resistance and the current = 15.2 per cent for this case, which should be compared with the value by wave formula of 15.7.

The results cannot be in perfect accord, however, for in view of the drop in the line, the leading and lagging energy cannot be exactly balanced at all points. The leading energy varies from point to point, while the lagging energy is substantially constant. The leading and lagging energy are here equal at the middle of the line.

Another example will illustrate a 60-cycle line. Assume a 300-mile transmission, with conductors of a diameter $\frac{1}{2}$ that of No. 0000 wire, spaced 10.5 ft. With a delivered voltage of 100,000 volts and load power-factor of 0.80 and delivered power of 12,000 kw. three phase, the drop at 60 cycles will be 6.2 per cent and the true loss 4.5 per cent (see *m*, Table A). The power-factor of the generator is 0.87 leading. Here the leading energy greatly predominates and the heavy lagging load current is changed into a leading current at the generator. The drop is satisfactory but the power transmitted is small. If the power is increased to 20,000 kw. the drop becomes 20.2 per cent, which is excessive although the line energy loss is small (see *n*, Table A). The generator power-factor becomes 0.998.

Again in this case the leading energy predominates. The drop would here be improved if there were synchronous machines at the lowering end of the line to carry the lagging current of the load.

If, however, the divided conductor arrangement be used—three parts for each conductor spaced 18 in. apart—the inductance and capacity will each be changed in the ratio 0.59 (see formula in companion paper). Choosing now a power delivered such as to balance the leading and lagging energy at the center of the line, that is 50,000 kw., the drop will be 14.5 per cent and the generator power-factor unity as well as the load power-factor (see case *o*, Table A). The line-loss is 14.8 per cent and the load current of 250 amperes becomes 250.7 at the generator. This is another excellent example of the effect of a close equality between leading and lagging energy.

The cost of line copper per kilowatt in this case with copper at 16c. is about $22, a reasonably small value.

In this connection it is interesting to compare the transmission curves given by Mershon in a paper before the Institute.* Here Mershon studies the economical conditions of power transmission as indicating the commercially feasible limits of distance. Mershon has tacitly assumed that the effect of the alternating character of the current on regulation can be ignored in his discussion by taking the line-drops as the product of the resistance by the current. Such an assumption will ordinarily be unjustifiable, for with the usual spacing of conductors the line-drop will be far from these ohmic values. With the actual values shown by Mershon's curves, however, the relations are such that for the long distances the leading and lagging energies are not very far apart. For example, the case *c*, Table A comes very closely to his curves. In other cases, however, especially the short distances, the lagging energy will greatly predominate, giving much larger line drops than those shown in Mershon's curves. It should be said, however, that in these cases the drop is relatively small on account of the short distances.

Mershon states that he uses synchronous machines to bring his average line power-factor to unity. What he does is to reduce by this means the power-factor of the energy at the middle or some other point of the line to unity, for this is the only power that the synchronous machine possesses. It cannot balance the leading and lagging energy of the line itself, as distinguished from the leading or lagging current of the load. As already explained, unity power-factor alone does not give the condition which will permit the transmission of power with a purely ohmic line drop, but the equality of leading and lagging energy within the line itself must also be obtained. Now, as has been shown above, this equality can in most cases of important transmissions be approximately obtained, by the proper choice of voltage and power transmitted and of relative line conductor arrangements; and the bad effects of the leading current building up a rise on light loads can be eliminated by supplying the leading energy from the receiving end of the line, so that the Mershon condition of direct-current drop can be quite nearly attained by these expedients. It is a matter for comment that the Mershon curves chosen for reasons of economy come rather near, in the maximum cases, to the best conditions for internal line conditions. This equality is departed from in the shorter distances, however.

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* Maximum Distance to which Power Can be Economically Transmitted, A. I. E. E. Transaction, Vol. XXIII, 1904, p. 759.

In the above discussion only the simple direct principles involved have been considered, since in this way they are most clearly pointed out. In most practical transmission systems these simple principles, while still perfectly true, are often dominated by naturally unfavorable proportions or by other features. Even in the long high-power lines where the line is the most important feature, many limiting conditions will often be found to prevent the realizing of ideal conditions. For example, the effect of leading current in the fields of synchronous generators is marked, and in the absence of automatic regulation will cause voltage variations. For this work in important cases possibly machines especially designed to hold the voltage constant might be desirable. The difficulty of obtaining the desired division of leading current among a number of stations may be troublesome, especially where the sub-stations are under independent control. Several lines of different lengths radiating from the same power house or those that are cross-connected may be troublesome. But it is the object of the present discussion to point out the principles governing the electrical action of the line, and not to discuss the secondary questions inevitably brought up by applications in special cases.

In calculations of lines in which the leading and lagging line energies are approximately equal, the split-capacity formula should not be used without great caution, for then it naturally has a large error especially in the value of line-drop. That this error will exist is evident from the fact that while in the line itself the effects of capacity and inductance are eliminated, the split-capacity formula shows an entirely different condition. Table I in the companion paper shows a number of cases calculated by both formulas. The close agreement in some instances with the wide divergence in others is notable.

Terminal apparatus. Much depends on the type and adjustment of the terminal apparatus, generators, motors, and synchronous converters, in controlling the line voltage, energy-loss and power-factor.

The object to be attained by the choice of type and method of control of the terminal apparatus, in addition to the generating and delivering of power, is the controlling and minimizing of line-drop and line energy-loss. As already pointed out, the terminal machines may control the line voltage by controlling the amount of charging current fed from the respective ends of the line. This is the same thing as controlling the power-factor at these points; for leading current to the line is the same as lagging current from the line to the apparatus.

It is important to bear in mind that one sort of terminal machines may be desirable when the power-factor adjustments are to be made by hand, another sort when it is desired to make the adjustments as far as possible automatic. The simplest case above was that in which the charging current is largely supplied from the receiving end.

The advantage of the non-synchronous generator at the power house in such a case is evident; for it will automatically throw the charging current; that is, the charging current over and above its own magnetizing current, on the synchronous machines at the load end. Since most large transmissions will have a steam auxiliary at the load end, this can to great advantage utilize synchronous type generators and supply the charging current of the line, except for a certain definite portion that will be supplied necessarily by the magnetizing current of the non-synchronous machine at the power-house end. This partial charging current from the power end is of advantage at full load, as it tends to reduce the ohmic drop. If desired, the non-synchronous machine can be made to take a relatively large magnetizing current for this purpose. But for the light load condition, the charging current should be fed largely from the load end, and this is to some extent automatically accomplished by the fact that at low load the non-synchronous machine takes less magnetizing current. But the dominating effect is the setting free at no load of the leading energy that was neutralized by the lagging energy of the line at full load, which causes the desired no-load rise in voltage toward the power house, and which is depended on to match the full-load drop toward the load end.

The use of non-synchronous machines has other advantages than this of allowing a definite automatic distribution of the charging current for the line, prominent among which are a number of mechanical and other advantages discussed in a paper by

Waters.* The non-synchronous machine at the power house gives another advantage, in that any tendency for excessive rise of potential at the power house will cause a greatly increased magnetizing current in the machine, that is, charging current to the line, which will help to keep down the rise of potential, since it will tend to cause a slope of potential along the line in the opposite direction. The limiting of the tremendous amount of short-circuit current that flows from large systems, through the well-known action of these non-synchronous machines, deserves special mention. Again, the fact that such machines need not be synchronized may be a very great advantage. While the paralleling of synchronous generators in a normal power house has no great difficulty or drawbacks, the separation of such machines by long distances is a great handicap, and the advantage of the non-synchronous machines here is noteworthy. While this is an operating advantage only, as such it is entitled to the fullest consideration.

Since even with a non-synchronous generator it is necessary to have accurate adjustment in the speed of the machine to avoid a sudden rush of current, and since in any case the throwing in of a large unit is always a disturbing factor, it is suggested that if a non-synchronous generator be used at the power house, load circuit-breakers be omitted, and that the step-up transformers and the generators be treated as a part of the line.

In some ways it is disadvantageous that the magnetizing current for the non-synchronous generator should come from the receiving end, as the power house would consequently be dependent on the distant station for excitation. In normal operation, however, the load will be continuous and there will normally always be magnetizing current available, while for emergencies a synchronous type of generator of the necessary capacity to handle one line may be installed at the power house. Such a generator could then be used for local power, if the power-house voltage should be found too variable.

In case *a*, Table A, the generator power-factor is 0.96 leading, which is suitable for a large non-synchronous generator under favorable speed conditions. Thus such a generator, with the assumed synchronous apparatus at the load end, could supply the line under the conditions assumed with the voltage drop and line-loss shown in this case. If the load were thrown off, the voltage would rise toward the power house (as the major portion of the line charging current would be supplied from the synchronous machines at the load end; that is, all but the magnetizing current of the non-synchronous machine) and to an amount not far from the full-load drop.

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* Waters, Trans. A. I. E. E., Vol. xxviii, p. 157, 1908.

Cases *e* and *g* and *h*, Table A,--all have leading line power-factors at the power house end, which, by a slight increase or decrease, would be suitable for a non-synchronous machine.

In these cases the voltage on no load would be little different, as in case *a*. To show the effect of intermediate loads, case *i*, showing the effect of two-thirds load in case *h*, has been calculated, giving a drop from power house to load end of 17.5 per cent, the lagging current of the non-synchronous machine at the power house being assumed to be slightly reduced.

In many ways the plan of having the system controlled at the receiving end has great operating advantages. This arrangement is simplest with auxiliary prime movers at the receiving end. It is possible, however, to accomplish similar results with synchronous motors.

The natural location for the control of a system, from the point of view of the service, is the receiving end; the custom of control from the power house ordinarily results from the greater complication of the apparatus at this point. If the use of non-synchronous machines should render the transfer of control to the receiving end feasible, this would be a welcome change.

Again it is certainly advantageous to have the voltage controlled at the load end rather than at the generator end of the line. An automatic regulator may be used on the machines at the load end to keep the voltage constant on the receiving busbars for practically all load variations. What variations of potential do occur would then be at the power house, where they would ordinarily be of relatively little consequence.

It may be said in favor of using synchronous machines at both ends of the line, that they permit much greater flexibility of adjustment of the relative amounts of leading current furnished by each and thus greater flexibility in the line control. The synchronous machines can of course take either a leading or a lagging current at will. The very flexibility of this system is perhaps its weakness, for the attendants at all points must work intelligently and in harmony, while with the non-synchronous machines the control is automatically thrown to the synchronous machine.

In smaller transmissions it will usually not be worth while to use machines of either type at the receiving end, as is shown by present practice, in which case only synchronous machines can be used at the power house.

General limitations. The limitations of a method of design or operation usually require more careful consideration than its merits, and the more important of the conditions limiting the methods here proposed will be considered It is a fact, however, that the weighing of advantages and disadvantages is very unsatisfactory in a general case, as the particular conditions of each system are a most important factor.

With such a close adjustment of proportions as is necessary for the most economical results theoretically, departures from the ideal condition may produce relatively large discrepancies. For example, in the full-load condition with leading and lagging energies balanced, overloads will add very rapidly to the drop; similarly, with a lowering of the power-factor required of the line at the receiving end. With the arrangement utilizing the auxiliary machines at the receiving end and non-synchronous machines at the power house, however, the variation of power-factor will be cared for automatically by the machines at the load end. If the line design be made approximately correct for the worst condition to be met; that is, full load at the lowest power-factor, so that the leading and lagging energies of the line are balanced, and if the drop is then not excessive and the non-synchronous machines or other generators at the power house take their correct amount of current, conditions should be stable.

A tendency to instability is inherent in any system in which the main generators do not assist in maintaining the voltage, such as systems using non-synchronous generators. Synchronous machines are notably at a disadvantage with lagging or leading current in the matter of voltage regulation, as such currents tend to demagnetize or strengthen the fields. If, then, the system is such that a relatively small machine must carry all the leading or lagging current for machines of much larger capacity, the tendency to instability is greatly increased. This will undoubtedly be one of the features requiring most careful consideration in such a system as here proposed. Special designs of synchronous machines would help somewhat. A quick-acting automatic regulator may be used to control voltage variations within reasonable limits in view of the sluggishness of large generator fields.

In the partial load or light load conditions the line-drop will be very sensitive to the relative amount of charging current supplied from the respective ends of the line, a greater portion from the power-house end causing a tendency toward a lessened drop toward the load end. With conditions tending to considerable variations, as they do in a large system, this fact will be a menace of line voltage variations. This again shows the value of automatic or semi-automatic control of the charging current distribution. On the other hand, it is clear that by properly proportioning the relative amounts of charging current supplied from the two ends of the line, an adjustment of the relative full-load and no-load voltage drops can be obtained and the two made equal. This adjustment can be much facilitated with non-synchronous generators by providing non-automatic means for adjusting the amount of lagging current at the power house. Separate adjustable-shunt lagging coils can be provided if desired.

On less than full load, the leading line energy and the lagging line energy no longer being equal, the most favorable conditions for economy of line loss no longer exist, and in the lighter loads the charging current or leading energy in the line materially increases the line energy loss. This condition can be reduced only by feeding charging current from both ends of the line, or even from three or more points along the line. The maximum charging current flowing at any point of the line will then be only that necessary to charge a fractional part of the whole.

In this matter of the added light-load line-energy loss, the divided conductor is at a disadvantage on account of its increased capacity and charging current. Thus in planning the line it is necessary to consider prominently the load at which the system is to run for the major portion of the time.

If the no-load voltage at the ends of an exceptionally long high-frequency line be adjusted to approximate equality by feeding charging current from both ends, and the voltage rise at the middle of the line is excessive, this can be corrected by feeding charging current also at the middle of the line either from synchronous or non-synchronous machines or from choke-coils.

Limitations will also be introduced by the layout of the system. A large plant of the type here under discussion would require at least two and probably three transmission lines, and with such large amounts of power as would be necessary to give economical financial conditions, two or three generators would be required for each line. In this case the interchanging of generators and loads between lines, if not carefully planned, might disturb the best adjustments of line and the regulation.

Again, when two separate sub-stations are fed from the same power house, changes of load and of field adjustment in synchronous generators at the two sub-stations would tend to cause overloading of one or the other of these machines and also a certain voltage variation.

Many special cases can be imagined in which will appear limitations and difficulties of varying importance in the use of the principles here discussed. Each case must be judged on its own merits, but the chief difficulties directly introduced have been pointed out.

The ratio of the leading and lagging line energies can be controlled, if desirable, by adding capacity in the form of condensers or synchronous types of machine across the line at sufficiently frequent intervals, or by similarly adding inductance by coils or machines. The coils might be added in series with the line, in which case they will tend to balance the leading energy for one load only, as with the normal line inductance, while with the shunt coils the leading energy is balanced for all loads and all voltages. These coils and condensers must be at sufficiently frequent intervals, the more frequent the more perfect their action. This use of distributed coils or condensers is analogous to that of the well-known Pupin load coils for telephone circuits.

The method of controlling the ratio of line inductance to line capacity by dividing conductors should receive fuller consideration. The electrical effect of dividing the conductor is not difficult to calculate approximately, and a suitable approximate formula is derived in the companion paper, formulas being given for the two-part and three-part divisions. The maximum practical numerical variation in favorable cases will be a reduction in the inductance and an increase in the capacity by the factor 2, obtained by the use of the three-part division. This gives an actual change in the ratio of capacity to inductance of 4. This is a little greater than will usually be easily realized. More or less serious mechanical difficulties are introduced by this construction, but these are by no means insuperable. It is probable that such an innovation will not be worth while, except in large, long, and important systems with relatively large conductors.

The divided parts of the conductors may be spaced equally and run straight and parallel to the line, or may be arranged spirally. They may be kept at the same spacing from one another at all points, or may be brought together at the insulators for mechanical support. They can be easily spaced by spreaders on the spans.

A certain mechanical reliability is introduced by the multiple conductors, in that if one is broken, through some defect in the wire, for example, the others will hold it up. With suspension-type insulators the supporting of multiple conductors will be mechanically relatively easy.

The wind and ice strains will be materially increased with the split conductors, but this fact will not necessarily be prohibitive: first, when the alternative will be an entirely new line on account of excessive drop, which will be still more expensive; secondly, with large conductors, since in such cases (where this method will be most useful) the wind strain, being relatively small in proportion to the weight and at right angles to the weight, will not add materially to the total, and since the ice strain will also be a much less important relative quantity than with the smaller wires, or may be absent entirely.

With two conductors the exposed area will of course be 1.4 times as great as with the same copper in one conductor. With three conductors the increase of surface will be 1.7.

The element of mechanical handling and stringing with very large conductors may work out in favor of divided conductors. In some cases it may be desirable to support each of the conductors on a separate insulator. This would give a distinct advantage in reliability, for if any one insulator should be shattered or the wire burn off, as in the case of a lightning ground, the others might support and insulate the line. This result, of course, assumes the automatic clearing of the line when the accident happens.

Again, the two or three divided conductors might be carried separately and insulated from one another all the way, being paralleled only at suitable points and mounted on separate insulators. In this case, under favorable conditions one bad conductor could be cut out and the others carry the current with a slightly increased loss. This arrangement has some advantages in maintaining continuity of service in a system exposed to lightning, for it is not likely that all three wires will be broken down simultaneously. In one sense, this arrangement has the flexibility of three circuits, for separate loads can be carried on the three wires provided they are fed from the same bus-bar. They could also feed separate step-down transformers and be paralleled again on the low-tension distributing bus-bar. The tower for such an arrangement would be only slightly larger than that for the single circuit. Of course numerous objections to these various arrangements will appear. Several other arrangements are possible, though perhaps of doubtful practicability.

To show the electrical advantage of the change of ratio of capacity to inductance even where it is not practicable to balance leading and lagging line energy, cases *k* and *l*, Table A, have been calculated. In a 300-mile, 25-cycle transmission, the drop is reduced from 17.1 to 11.4 per cent and the generator power-factor is raised from 0.876 to 0.97.

A number of principles have been here considered, bearing directly on the allowable output and the regulation of long transmission lines. The subjects have been treated in an entirely general way, no effort being made to apply them to a particular installation. The writer wishes to point out that many of the possible arrangements mentioned have been added merely to illuminate the subject and not with the thought that they will be embodied in actual installations. Any particular plant must be a compromise, meeting in the best way the various more or less conflicting demands of full load and light load, voltage regulation, line energy-loss, output and cost of generators, and of line load-factor, operating simplicity, and climatic conditions.

The effectiveness of this proportioning of inductance and capacity in eliminating the effects of capacity and inductance in the transmission line, suggests its application in other work, as for example, submarine cable work. Here the conditions are different, for it is necessary to deal largely with the transient phenomena, and, further, instead of the line voltage being substantially a constant, it will vary from a maximum to zero, thus tending to give a constantly varying ratio between the leading energy and the lagging energy. Since the electrostatic capacity of the cable greatly exceeds the inductance, an increase of inductance will be required to obtain the necessary balance. This matter will not be treated further here.

SUMMARY

The more important definite conclusions arrived at may be summarized as follows.

1. To obtain the most economical transmission of power over a long-distance line, it is necessary to have balanced the leading and lagging energies of the line itself, and at the same time to have unity power-factor, in which case the transmission is similar to direct-current both as to voltage-drop and energy-loss.

2. The power-factor at the load end may be made unity or otherwise controlled by synchronous machines, generators or motors, located at the receiving end of the line.

3. To obtain satisfactory regulation for high-power long-distance transmission, the leading current taken by the line at light loads should be fed mainly from the receiving end. By this means the voltage-rise from the receiving end; that is, the drop from the power house to the receiving end, can be kept nearly constant for all loads. Adjustment of the line-drop can be accomplished at any load by varying the amounts of the leading energy or charging current supplied to the respective ends of the line.

4. The voltage regulation and line-losses may be controlled for any commercial frequency and for any percentage load condition—as far as its electrical action is concerned—using a conductor of sufficient section, by making the leading and lagging line-energies equal at full load, and by feeding suitable proportions of the charging current at other loads from the respective ends of the line, the greater portion being from the receiving end.

5. The adjustment of the leading and lagging energies taken by the line itself may be accomplished by the choice of voltage and load, or by adjusting the ratio of the capacity and inductance of the line. The latter adjustment can be accomplished effectively by dividing the conductors and spacing them apart a reasonable distance.

6. Calculations of these long high-voltage, high-power lines may be made approximately only by formulas founded on the assumption of localized capacity. The error in the voltage may be several per cent. The approximate formulas are especially unreliable when the leading and lagging energy in the line are equal.

7. Non-synchronous generators are suggested for the power house of a long high-power transmission where it is desired to supply the leading energy for the line from the receiving end. The latter then becomes the controlling and operating point of the system.

8. Constant voltage or suitable compounding should then be maintained at the receiving end and not at the generating end of the system, thus practically eliminating line voltage regulation as a disturbing factor.

9. While it is possible by a cut-and-try method for any given case to arrive at the best condition of capacity, resistance, inductance, and the power-factor at the load end of the line, yet the best result will be obtained most directly by planning the line in accordance with the principles here explained.

While comparatively few high-tension power-transmitting systems now installed are of sufficient magnitude to require as careful a treatment as that outlined here, the development of this art cannot proceed much further without some such method. It is the hope of the writer that here, either directly or, perhaps more likely, by suggestion, he has somewhat forwarded this development.

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CALCULATION OF THE HIGH-TENSION LINE *

BY PERCY H. THOMAS

Neglecting matters of cost, the electrical performance of the high-tension transmission line becomes the critical factor as the quantity of power and distance of transmission become large. The loss and variation of voltage and, to a lesser extent, perhaps, the loss of energy in the line tend to become the dominating features. A careful study of these characteristics is thus most important in planning such a transmission. It is the purpose of the present paper to discuss the calculation of the high-tension line as relating to the important matters of regulation and energy line loss, and with especial reference to the unusually long and high-power lines. For this purpose certain new formulas suited for practical calculations are derived.

While it has been freely recognized that, strictly speaking, calculations of line quantities should, where appropriate, be made in such a manner as to take cognizance of the fact that the capacity, inductance, and capacity of the line are distributed uniformly, the difficulty of such calculations and the lack of suitable formulas have led to the use of approximations. It may be said that many of these approximations are sufficiently accurate for all ordinary commercial systems. However, in large and very long-distance transmissions the error introduced by the approximations becomes quite noticeable, and while not great enough to threaten seriously the usefulness of the system is too great for a conscientious engineer to neglect.

In the following pages is derived a formula for calculating the true current, voltage, and power-factor at the generator end of a transmission line when the current, voltage, and power-factor at the receiving end are known. This formula is especially adapted to slide-rule work and when once familiar requires relatively little labor.

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* It is intended that this paper shall be considered in connection with a companion paper presented at the same time and entitled "Output and Regulation in Long-Distance Lines."

This formula reduces to the usual well-known forms when the resistance, inductance, or the capacity is put equal to 0.

For purposes of comparison an approximate formula is given, used by the writer and based on the much used assumption that the line capacity is concentrated at the ends of the line. This is called the " split-capacity " formula in distinction from the " wave " formula with the distributed capacity first mentioned. The split-capacity formula is exceptionally simple and readily used with a table of cosines and tangents and is believed to be as accurate as any available approximate formula; it would be perfectly accurate were the capacity actually located at the ends of the line as assumed.

To show the relation numerically of the results given by the split-capacity and the wave formulas, Table I is added showing the actual numerical values for a number of selected cases.

The conditions which tend to make a large discrepancy between the two formulas are length, high frequency and low resistance, as well as the particular relation of capacity and inductance energy in the line.

The last column of the table gives the actual phase change due to the time consumed in the passage of the wave through the length of the line as is represented by the quantity $\frac{px}{v}$

DERIVATION OF WAVE FORMULA

Current flow in a uniform conductor containing inductance, capacity, and resistance, distributed, obeys the following laws:

1. Current flowing through resistance produces a drop equal to the product of the current and the resistance at any instant.

2. A varying current produces in an inductance an electromotive force proportional to the rate of change of the current and to the inductance and opposing the current variation.

3. The current to a condenser is proportional to the rate of increase of potential and to the capacity.

From these laws it follows that at any instant

$$\frac{d^2 V}{d x^2} = C R \frac{d V}{d t} + C L \frac{d^2 V}{d t^2} \qquad (1)$$

TABLE I.

COMPARISON OF FORMULAS.

	Distance in miles	Size of conductors	Spacing of conductors	Transmitted power, three-phase	Line voltage delivered	Line current load end, "–" means leading 1 φ equivalent	Frequency	Line power-factor, load end	Voltage drop in % of gen. voltage	Line energy loss in % of generator power	Line power-factor gen. end, "–" means leading	Line current, generator end 1 φ equivalent	$\frac{\phi x}{v}\left(\frac{360}{2\pi}\right)$	Type of Formula
A	150	#000	7	10000	80000	73.5	25	0.85	10.2	8.6	0.922	66.6	8° 9′	Wave
B	"	"	"	"	"	"	"	"	10.0	8.6	0.920	67.0	—	Sp't Cap.
C	"	"	"	"	"	"	"	"	12.6	7.6	0.985	60.1	18° 13′	Wave
D	"	"	"	"	"	"	60	"	12.9	7.7	0.984	60.1	—	Sp't Cap.
†*E*	700	2 #00	10	40000	150000	142.5	25	0.935	20.5	20.4	–0.950	140.0†	35° 29′	Wave
F	"	"	"	"	"	"	"	"	22.7	20.1	–0.948	136.4	—	Sp't Cap.
G	"	"	"	0	"	–63.8	"	—	1.1	—	—	—	35° 29′	Wave
H	"	"	"	"	"	"	"	—	1.0	—	—	—	—	Sp't Cap.
I	"	3 #0000	12	40000	150000	145.3	25	0.918	12.1	10.4	–0.963	134.8	34° 48′	Wave
K	"	"	"	"	"	"	"	"	13.5	9.5	–0.968	131.5	—	Sp't Cap.
L	"	"	"	60000	"	200	"	1.00	11.5	13.8	–0.994	206.8	34° 48′	Wave
M	"	"	"	"	"	"	"	"	14.1	14.7	–0.996	202.7	—	Sp't Cap.
N	"	"	"	"	"	202	60	0.99	7.2	13.2	–0.974	219.7	83° 6′	Wave
O	"	"	"	"	"	"	"	"	34.0	17.8	–0.941	170.7	—	Sp't Cap.
P	"	$(3\frac{1}{4}) \times$ #0000	*D** "	75000	"	278	25	0.90	19.6	13.7	–0.988	237	35° 6′	Wave
Q	"	"	*D** "	"	"	"	"	"	25.6	13.8	–0.998	215.7	—	Sp't Cap.
R	75	#0000 lead cable	‡	12000	40000	187.5	"	0.80	15.5	15.7	0.973	154.3	13° 34′	Wave
S	"	"	"	"	"	"	"	"	15.3	15.5	0.973	154.3	—	Sp't Cap.
T	300	$(\frac{3}{2})^2 \times$ #0000	10.5	20000	100000	125	60	"	20.2	7.0	0.998	86.1	35° 36′	Wave
U	"	"	"	"	"	"	"	"	21.9	6.9	0.996	84.3	—	Sp't Cap.
V	"	"	"	12000	"	75	"	"	6.2	4.46	–0.873	67.5	35° 36′	Wave
W	"	"	"	"	"	"	"	"	7.4	3.9	–0.89	64.8	—	Sp't Cap.
†						142.5	25	93.5	13.9	11.0	1.000	129.0	17° 45′	Wave

† Condition at middle of line,

*D** means divided conductor—each line wire divided into three separate conductors spaced 18″ apart.

‡ Assumed constants, $R = 0.515$, $p\,L = 0.264$, $p\,C = 0.00002358$, all per mile

where

V is the potential at any point of the conductor,
R, L, and C are its resistance, inductance, and capacity, respectively, per unit length,
x is the distance of any given point from the end.
t is the time, measured from any starting instant.

This equation may be arrived at as follows: The current flowing to any small element of capacity is $(C\,d\,x)\left(\frac{d\,V}{d\,t}\right)$ where $C\,d\,x$ is the capacity of the short length $d\,x$, see Fig. 1.

This represents the total current subtracted from the current flowing along the conductor to increase the charge in the small condenser $C\,d\,x$, corresponding to the increase in voltage $d\,V$ accomplished in the short time $d\,t$. This small current

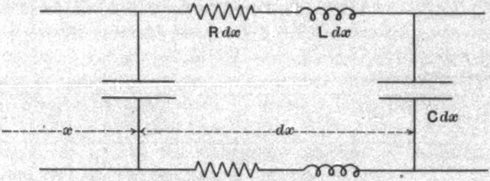

FIG. 1—Elementary section of transmission line.

$C\,d\,x\ \frac{d\,V}{d\,t}$ which is subtracted from the current already flowing, causes a resistance drop of

$$(R\,d\,x)\left(C\,d\,x\ \frac{d\,V}{d\,t}\right),$$

since the resistance of the short length $d\,x$ will be $R\ d\,x$. Similarly since the condenser current also flows through the inductance $L\,d\,x$ it will produce a counter voltage

$$(L\,d\,x)\ \frac{d}{d\,t}\ \left(C\,d\,x\ \ \frac{d\,V}{d\,t}\right) = C\,L\,d\,x^2\,\frac{d^2\,V}{d\,t^2}$$

Thus

$$R\,C\,d\,x^2\ \frac{d\,V}{d\,t} + L\,C\,d\,x^2\ \frac{d^2\,V}{d\,t^2}$$

gives the voltage caused in the length $d\,x$ by the current flowing to the capacity $C\,d\,x$.

But the voltage difference between the points $x+d\,x$ and x

is $(d\,x)\left(\frac{d\,V}{d\,x}\right)$

This voltage difference, however, includes the drop due to the total current flowing in the conductor and not the *variation* of the total drop which is caused by the charging current

$C\,d\,x\,\frac{d\,V}{d\,t}$, alone.

Therefore, this *increase* of the total drop due to the current

$C\,d\,x\,\frac{d\,V}{d\,t}$ in the length $d\,x$ will be proportional to the rate of

increase of

$$d\,x\,\frac{d\,V}{d\,x},\ \text{that is,}\ d\left[d\,x\,\frac{d\,V}{d\,x}\right] = d\,x^2\,\frac{d^2\,V}{d\,x^2}$$

Therefore we have the equation

$$d\,x^2\,\frac{d^2\,V}{d\,x^2} = R\,C\,d\,x^2\,\frac{d\,V}{d\,t} + L\,C\,d\,x^2\,\frac{d^2\,V}{d\,t^2}$$

or dividing by $(d\,x)^2$

$$\frac{d^2\,V}{d\,x^2} = R\,C\,\frac{d\,V}{d\,t} + L\,C\,\frac{d^2\,V}{d\,t^2} \qquad (1)$$

This is the usual differential equation for such a circuit. It has been derived, integrated and discussed by many authors, during the last twenty years or more—including Vaschy, Heaviside, Bedell, Pupin, Leblanc and Steinmetz, the latter three in the Institute Transactions.* All these authors have given solutions in such a general form as to be very awkward for use in connection with actual circuits for numerical computation. Steinmetz and Leblanc, and presumably the others, have given the necessary equations by which the specific conditions for a given problem can be worked out, but this only at great labor.

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* Pupin, Vol. xvii, A. I. E. E. 1900, p. 445.
Leblanc, Vol. xix, A. I. E. E. TRANSACTIONS, p. 759.
Steinmetz, Vol. xvii, 1908, p. 1231.

To return to the derivation of the formula. Having given the above differential equation, it is necessary to find a form of equation without differential quantities, which when differentiated will satisfy this equation (1); that is, to find its primitive. This will be a matter of trial. The above writers have pointed out some suitable forms and of these the most convenient for this case is that of LeBlanc* and Vaschy as follows:

$$V = \varepsilon^{\alpha(l-x)} \left[A \sin \left(p\,t - \frac{p\,x}{v} \right) + B \cos \left(p\,t - \frac{p\,x}{v} \right) \right]$$
$$+ \varepsilon^{-\alpha(l-x)} \left[D \sin \left(p\,t + \frac{p\,x}{v} \right) + F \cos \left(p\,t + \frac{p\,x}{v} \right] \right. \qquad (2)$$

where

l = length of the line.

x the distance from the start

$p = 2\,\pi\,n$ (n = frequency), and where v and α are constants which must be determined to make equation (2) consistent with the differential equation (1). This equation giving the voltage at any point of the circuit will always satisfy the differential equation (1) with such suitable values for the constants α and v. The constants A, B, D, and F, are the constants of integration and can be determined when the terminal voltages or terminal currents are known sufficiently to make the problem actually determinate. In other words equation (2) will be consistent with the differential equation with any values of A, B, D, and F.

This equation (2) is not the most general possible form of primitive equation for the differential equation, since no factors occur having an exponential time function. This form is chosen purposely for the condition here to be studied; that is, the steady condition in which the voltage and current have been flowing long enough to reach a permanent condition, and all the starting disturbances have disappeared.

The value of α and v in equation (2) will next be determined to satisfy the differential equation (1).

The values of

$$\frac{d^2\,V}{d\,x^2},\ R\,C\,\frac{d\,V}{d\,t},\ \text{and}\ L\,C\,\frac{d^2\,V}{d\,t^2}$$

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*Le Blanc, A, I. E. E. TRANSACTIONS, Vol. xix, 1902, p. 759.

can be determined from equation (2) by differentiating

$$\frac{dV}{dt} = \varepsilon^{\alpha(l-x)}\left[pA\cos\left(pt-\frac{px}{v}\right) - pB\sin\left(pt-\frac{px}{v}\right)\right]$$

$$+\varepsilon^{-\alpha(l-x)}\left[pD\cos\left(pt+\frac{px}{v}\right) - pF\sin\left(pt+\frac{px}{v}\right)\right] \quad (3)$$

$$\frac{d^2V}{dt^2} = \varepsilon^{\alpha(l-x)}\left[-p^2A\sin\left(pt-\frac{px}{v}\right) - p^2B\cos\left(pt-\frac{px}{v}\right)\right]$$

$$+\varepsilon^{-\alpha(l-x)}\left[-p^2D\sin\left(pt+\frac{px}{v}\right) - p^2F\cos\left(pt+\frac{px}{v}\right)\right] \quad (4)$$

$$\frac{dV}{dx} = \varepsilon^{\alpha(l-x)}\left[\left(-\alpha A+\frac{p}{v}B\right)\sin\left(pt-\frac{px}{v}\right) + \left(-\alpha B-\frac{p}{v}A\right)\right.$$

$$\left.\times\cos\left(pt-\frac{px}{v}\right)\right] + \varepsilon^{-\alpha(l-x)}\left[\left(\alpha D-\frac{p}{v}F\right)\sin\left(pt+\frac{px}{v}\right)\right.$$

$$\left.+\left(\alpha F+\frac{p}{v}D\right)\cos\left(pt+\frac{px}{v}\right)\right] \quad (5)$$

$$\frac{d^2V}{dx^2} = \varepsilon^{\alpha(l-x)}\left[\left(\frac{\alpha^2v^2-p^2}{v^2}A-\frac{2\alpha p}{v}B\right)\sin\left(pt-\frac{px}{v}\right)\right.$$

$$\left.+\left(\frac{2\alpha p}{v}A+\frac{\alpha^2v^2-p^2}{v^2}B\right)\cos\left(pt-\frac{px}{v}\right)\right]$$

$$+\varepsilon^{-\alpha(l-x)}\left[\left(\frac{\alpha^2v^2-p^2}{v^2}D-\frac{2\alpha p}{v}F\right)\sin\left(pt+\frac{px}{v}\right)\right.$$

$$\left.+\left(\frac{2\alpha p}{v}D+\frac{\alpha^2v^2-p^2}{v^2}F\right)\cos\left(pt+\frac{px}{v}\right)\right] \quad (6)$$

The differential equation (1) must be satisfied by these values so that substituting in equation (1) and rearranging terms, we have

$$\varepsilon^{\alpha(l-x)}\left[\left\{\frac{\alpha^2v^2-p^2}{v^2}A-\frac{2\,\alpha\,p}{v}B-R\,C\,(-p\,B)-L\,C\,(-p^2A)\right\}\right.$$

$$\times\sin\left(p\,t-\frac{px}{v}\right)+\left\{\frac{2\alpha\,p}{v}A+\frac{\alpha^2v^2-p^2}{v^2}B-RC(p\,A)-LC(-p^2B)\right\}$$

$$\left.\times\cos\left(p\,t-\frac{px}{v}\right)\right]$$

$$+\,\varepsilon^{-\alpha(l-x)}\left[\left\{\frac{\alpha^2v^2-p^2}{v^2}D-\frac{2\,\alpha\,p}{v}F-R\,C\,(-p\,F)-L\,C\,(-p^2D)\right\}\right.$$

$$\times\sin\left(p\,t+\frac{px}{v}\right)+\left\{\frac{2\,\alpha\,p}{v}D+\frac{\alpha^2\,v^2-p^2}{v^2}F-RC(pD)-LC(-p^2F)\right\}$$

$$\left.\times\cos\left(p\,t+\frac{px}{v}\right)\right]$$

$$=0$$

This equation must be true for all values of t and for all values of x and for all values of A and B and D and F. This can be true only when each of the four coefficients of the sine and cosine terms is 0.

Therefore

$$\left(\frac{\alpha^2v^2-p^2}{v^2}+p^2\,L\,C\right)A+\left(-\frac{2\,\alpha\,p}{v}+p\,R\,C\right)B=0$$

$$\left(\frac{2\,\alpha\,p}{v}-p\,R\,C\right)A+\left(\frac{\alpha^2\,v^2-p^2}{v^2}+p^2\,L\,C\right)B=0$$

$$\left(\frac{\alpha^2\,v^2-p^2}{v^2}+p^2\,L\,C\right)D+\left(-\frac{2\,\alpha\,p}{v}+p\,R\,C\right)F=0$$

$$\left(\frac{2\,\alpha\,p}{v}-p\,R\,C\right)D+\left(\frac{\alpha^2\,v^2-p^2}{v^2}+p^2\,L\,C\right)F=0$$

But these equations can be zero for all values of A, B, D and F, only if the coefficients of each of these later quantities = 0.

That is

$$\frac{\alpha^2\,v^2-p^2}{v^2}+p^2\,L\,C=0 \qquad (7)$$

$$\text{and}\ \frac{2\,\alpha\,p}{v}-p\,R\,C=0 \qquad (8)$$

From equation (8),

$$\alpha = \frac{R\,C\,v}{2} \tag{9}$$

Substituting this value of α in equation (7) and multiplying both sides of the equation by $4\,v^2$

$$R^2\,C^2\,v^4 + 4\,p^2\,L\,C\,v^2 = 4\,p^2$$

$$v^4 + \frac{4\,p^2\,L}{C\,R^2}\,v^2 = \frac{4\,p^2}{C^2\,R^2}$$

$$v^4 + \frac{4\,p^2\,L}{C\,R^2}\,v^2 + \frac{4\,p^4\,L^2}{C^2\,R^4} = \frac{4\,p^2}{C^2\,R^2} + \frac{4\,p^4\,L^2}{C^2\,R^4}$$

$$v^2 = -\frac{2\,p^2\,L}{C\,R^2} \pm \sqrt{\frac{4\,p^2\,R^2 + 4\,p^4\,L^2}{C^2\,R^4}}$$

$$v = \pm\,\frac{1}{\sqrt{L\,C}}\,\sqrt{2\,p\,L\left(\frac{-p\,L \pm \sqrt{R^2 + p^2\,L^2}}{R^2}\right)}$$

multiplying numerator and denominator under the radical by

$$p\,L \pm \sqrt{R^2 + p^2\,L^2}$$

$$v = \pm\,\frac{1}{\sqrt{L\,C}}\,\sqrt{\frac{2\,p\,L}{p\,L \pm \sqrt{R^2 + p^2\,L^2}}} \tag{10}$$

Of the four possible values of v represented by the alternative signs and all satisfying the differential equation, only that involving the positive sign will satisfy the physical conditions of the transmission of current.

Equation (2), with equations (9) and (10), thus constitutes a formula, giving a variation of potential along a conductor such that current flow follows the laws of resistance, inductance and capacity, as laid down at the beginning of this discussion and as is shown by its satisfying the differential equation (1). This equation is perfectly determinate except for the four constants A, B, D, and F. If these are chosen in such a way that the equation represents the correct potential of the conductor at any one point, it will then represent it at all points.

Before determining these constants for a particular case, however, the equation for the current flow at any point of the same conductor will be determined. Referring to Fig. 1, it is clear that the decrease in the current between the points x and $(x+dx)$ is the capacity $C\,dx$ times the rate of change in voltage at this point, namely

$$(C\,dx)\left(\frac{dV}{dt}\right)$$

Thus, the total current will be

$$-\int\left(\frac{dV}{dt}\right)(C)\,dx+K=-C\int\frac{dV}{dt}\,dx$$

For the constant K will be zero, since it may be assumed that there is no current flow existing in the conductor, which is independent of time and space.

Equation (3) gives the value of $\frac{dV}{dt}$.

It is evident by inspection that this equation when integrated with respect to x will have the same form as equation (2) but with different coefficients for the sine and cosine terms. It will be simpler to differentiate such a general expression for the current with respect to x and equate the coefficients to those of the expression for

$$-C\,\frac{dV}{dt}$$

and from these determine the general coefficients assumed in the general equation of current, than to integrate

$$-C\int\frac{dV}{dt}\,dx \quad \text{directly.}$$

Assume, then, that the letters a, b, d and f represent the coefficients of the integrated curve of current, which is taken to have the same form as the equation of potential (2). Here the coefficient a of the current equation corresponds to A of the potential equation, b to B, etc. That is, we may consider that equation (2) is the new integrated current equation assumed, if the quantities A, B, D and F become a, b, d and f with new values. We have then to determine a, b, d and f of the current curve in terms of the quantities in the potential equation. If I is the current, then

$\frac{d\,I}{d\,x}$ will be the same form as equation (5),

but with the quantities a, b, d and f substituted for A, B, D and F. But

$$\frac{d\,I}{d\,x} = -C\,\frac{d\,V}{d\,t} = -\frac{d}{d\,x}\int C\,\frac{d\,V}{d\,t}\,d\,x, \text{ as above.}$$

Therefore the coefficients of the like sine and cosine terms must be equal in this latter equation, see equation (3), and in the modified equation (5).

Therefore

$$p\,C\,A = \frac{p\,a}{v} + \alpha\,b \tag{11}$$

$$p\,C\,B = \frac{p\,b}{v} - \alpha\,a \tag{12}$$

$$p\,C\,D = -\frac{p\,d}{v} - \alpha\,f \tag{13}$$

$$p\,C\,F = -\frac{p\,f}{v} + \alpha\,d \tag{14}$$

From equations (11) and (12),

$$a = p\,v\,C\,\frac{p\,A - \alpha\,v\,B}{p^2 + \alpha^2\,v^2}$$

$$b = p\,V\,C\,\frac{\alpha\,v\,A + p\,B}{p^2 + \alpha^2\,v^2}$$

From equations (13) and (14),

$$d = p\,v\,C\,\frac{-p\,D + \alpha\,v\,F}{p^2 + \alpha^2\,v^2}$$

$$f = p\,v\,C\,\frac{-\alpha\,v\,D - p\,F}{p^2 + \alpha^2\,v^2}$$

substituting these values of a, b, d and f in the equation for current we have

$$I = \frac{p\,v\,C}{p^2+\alpha^2 v^2}\Big[\varepsilon^{\alpha(l-x)}\Big\{\Big(p\,A-\alpha\,v\,B\Big)\sin\left(p\,t-\frac{px}{v}\right)+(\alpha\,v\,A+p\,B)\times\cos\left(p\,t-\frac{px}{v}\right)\Big\}+\varepsilon^{-\alpha(l-x)}\Big\{\Big(-p\,D+\alpha\,v\,F\Big)\sin\left(p\,t+\frac{px}{v}\right)-(\alpha\,v\,D+p\,F)\cos\left(p\,t+\frac{px}{v}\right)\Big\}\Big] \qquad (15)$$

the general current equation.

We may now determine the values of A, B, C, and D for the particular case here under discussion; namely, where we have given the current, and voltage, and angle of lag between them, at the receiving end of a conductor. When these constants are then determined, the calculation of the voltage and current and lag angle can be made by the voltage and current equations for any other point of the conductor.

Assume that the received voltage is

$$S\sin(p\,t+\theta)$$

and the received current is

$$Q\sin p\,t$$

Then if we assume (for convenience) that the receiving end is at the point $x = 0$, we have at the instant when $t = 0$ from equation (2) and equation (15)

$$V_0 = \varepsilon^{\alpha l}B+\varepsilon^{-\alpha l}F = \mathrm{S}\sin\theta \qquad (16)$$

$$I_0 = \frac{p\,v\,C}{p^2+\alpha^2 v^2}\Big\{\varepsilon^{\alpha l}(\alpha\,v\,A+p\,B)-\varepsilon^{-\alpha l}(\alpha\,v\,D+p\,F)\Big\} = 0 \qquad (17)$$

And when $p\,t = \frac{\pi}{2}$ we have

$$V_{\frac{\pi}{2}} = \varepsilon^{\alpha l}A+\varepsilon^{-\alpha l}D = S\cos\theta \qquad (18)$$

$$I_{\frac{\pi}{2}} = \frac{p\,v\,C}{p^2+\alpha^2 v^2}\Big\{\varepsilon^{\alpha l}(p\,A-\alpha\,v\,B)-\varepsilon^{-\alpha l}(p\,D-\alpha\,v\,F)\Big\} = -Q \qquad (19)$$

Q is negative, since normal current to the receiving circuit is in the negative direction in the line, as the receiving circuit is at the point $x = 0$.

From equations (17) and (19),

$$\varepsilon^{\alpha l}A - \varepsilon^{-\alpha l}D = -\frac{pQ}{pvC} \qquad (20)$$

$$\varepsilon^{\alpha l}B - \varepsilon^{-\alpha l}F = \frac{\alpha vQ}{pvC} \qquad (21)$$

From equations (18) and (20).

$$A = \frac{1}{2\varepsilon^{\alpha l}}\left(-\frac{pQ}{pvC} + S\cos\theta\right) \qquad (22)$$

$$D = \frac{1}{2\varepsilon^{-\alpha l}}\left(\frac{pQ}{pvC} + S\cos\theta\right) \qquad (23)$$

From equations (16) and (21),

$$B = \frac{1}{2\varepsilon^{\alpha l}}\left(\frac{\alpha vQ}{pvC} + S\sin\theta\right) \qquad (24)$$

$$F = \frac{1}{2\varepsilon^{-\alpha l}}\left(\frac{-\alpha vQ}{pvC} + S\sin\theta\right) \qquad (25)$$

and by substituting in equation (2), we have

$$2V = \varepsilon^{-\alpha x}\left[\left(\frac{-pQ}{pvC} + S\cos\theta\right)\sin\left(pt - \frac{px}{v}\right) + \left(\frac{\alpha vQ}{pvC} + S\sin\theta\right)\right.$$
$$\left.\times\cos\left(pt - \frac{px}{v}\right)\right] + \varepsilon^{\alpha x}\left[\left(\frac{pQ}{pvC} + S\cos\theta\right)\sin\left(pt + \frac{px}{v}\right)\right.$$
$$\left.-\left(\frac{\alpha vQ}{pvC} - S\sin\theta\right)\cos\left(pt + \frac{px}{v}\right)\right]$$

$$2V = \varepsilon^{-\alpha x}\left[\frac{Q}{pvC}\left\{\left(-p\sin\left(pt - \frac{px}{v}\right) + \alpha v\cos\left(pt - \frac{px}{v}\right)\right\}\right.$$
$$\left.+S\left\{\cos\theta\sin\left(pt - \frac{px}{v}\right) + \sin\theta\cos\left(pt - \frac{px}{v}\right)\right\}\right]$$
$$+\varepsilon^{\alpha x}\left[\frac{Q}{pvC}\left\{p\sin\left(pt + \frac{px}{v}\right) - \alpha v\cos\left(pt + \frac{px}{v}\right)\right\}\right.$$

$$+S\left\{\cos\theta\sin\left(pt+\frac{px}{v}\right)+\sin\theta\cos\left(pt+\frac{px}{v}\right)\right\}\Bigg]$$

$$2V=\varepsilon^{-\alpha x}\left[\frac{Q\sqrt{p^2+\alpha^2v^2}}{pvC}\left\{\cos\left(pt-\frac{px}{v}+\tan^{-1}\frac{p}{\alpha v}\right)\right\}\right.$$

$$\left.+S\sin\left(pt-\frac{px}{v}+\theta\right)\right]$$

$$+\varepsilon^{\alpha x}\left[\frac{Q\sqrt{p^2+\alpha^2v^2}}{pvC}\left\{-\cos\left(pt+\frac{px}{v}+\tan^{-1}\frac{p}{\alpha v}\right)\right\}\right.$$

$$\left.+S\sin\left(pt+\frac{px}{v}+\theta\right)\right]$$

but

$$\frac{\sqrt{p^2+\alpha^2v^2}}{pvC}=\sqrt{\dfrac{\dfrac{(pL+\sqrt{R^2+p^2L^2})^2+R^2}{(pL+\sqrt{R^2+p^2L^2})^2}}{\dfrac{pC}{pL+\sqrt{R^2+p^2L^2}}}}$$

from equations (9) and (10),

$$=\sqrt{\frac{\sqrt{R^2+p^2L^2}}{pC}}$$

Therefore

$$2V=\varepsilon^{-\alpha x}\left[Q\sqrt{\frac{\sqrt{R^2+p^2L^2}}{pC}}\left\{\cos\left(pt-\frac{px}{v}+\tan^{-1}\frac{p}{\alpha v}\right)\right\}\right.$$

$$\left.+S\sin\left(pt-\frac{px}{v}+\theta\right)\right\}\Bigg]$$

$$+\varepsilon^{\alpha x}\left[Q\sqrt{\frac{\sqrt{R^2+p^2L^2}}{pC}}\left\{-\cos\left(pt+\frac{px}{v}+\tan^{-1}\frac{p}{\alpha v}\right)\right\}\right.$$

$$\left.+S\sin\left(pt+\frac{px}{v}+\theta\right)\right\}\Bigg] \tag{26}$$

This equation shows the voltage at any point of a line of known resistance, capacity, and inductance, at any instant of time, assuming only that the steady condition has been reached and all starting oscillations have disappeared, and taking the current and voltage at the end of the line as, $Q\sin pt$, and, $S\sin(pt+\theta)$, respectively.

For the purposes of later discussion and for facilitating numerical computation it is convenient to put this equation into a somewhat different form.

Expanding the expressions $\sin\left(pt - \frac{px}{v} + \theta\right)$ and the similar terms, in the form $\sin\left\{\left(pt+\theta\right) \pm \frac{px}{v}\right\}$, etc.,

$$V = \frac{\varepsilon^{\alpha x}+\varepsilon^{-\alpha x}}{2}\left[\left\{Q\sqrt{\frac{\sqrt{R^2+p^2L^2}}{pC}}\sin\left(pt+\tan^{-1}\frac{p}{\alpha v}\right)\right\}\right.$$

$$\left.\times\sin\frac{px}{v}+\left\{S\sin(pt+\theta)\right\}\cos\frac{px}{v}\right]$$

$$+\frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2}\left[\left\{-Q\sqrt{\frac{\sqrt{R^2+p^2L^2}}{pC}}\cos\left(pt+\tan^{-1}\frac{p}{\alpha v}\right)\right\}\right.$$

$$\left.\times\cos\frac{px}{v}+\left\{S\cos(pt+\theta)\right\}\sin\frac{px}{v}\right] \qquad (27)$$

It is interesting to notice that the quantities $\frac{\varepsilon^{\alpha x}+\varepsilon^{-\alpha x}}{2}$ and $\frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2}$ are respectively the hyperbolic cosine and hyperbolic sine of αx respectively; that is, are $\cosh \alpha x$ and $\sinh \alpha x$, respectively.

Returning now to the current equation and substituting in equation (15), the values of the constants A, B, D and F as found in equation (22), (23), (24) and (25).

$$2I = \frac{pvC}{p^2+\alpha^2v^2}\left[\varepsilon^{-\alpha x}\left\{\left[p\left(-\frac{pQ}{pvC}+S\cos\theta\right)\right.\right.\right.$$

$$\left.-\alpha v\left(\frac{\alpha vQ}{pvC}+S\sin\theta\right)\right]\sin\left(pt-\frac{px}{v}\right)$$

$$+\left[\alpha v\left(-\frac{pQ}{pvC}+S\cos\theta\right)+p\left(\frac{\alpha vQ}{pvC}+S\sin\theta\right)\right]$$

$$\left.\times\cos\left(pt-\frac{px}{v}\right)\right\}$$

$$+\varepsilon^{\alpha x}\Big\{\Big[-p\Big(\frac{pQ}{pvC}+S\cos\theta\Big)+\alpha v\Big(\frac{-\alpha vQ}{pvC}$$

$$+S\sin\theta\Big)\Big]\sin\Big(pt+\frac{px}{v}\Big)-\Big[\alpha v\Big(\frac{pQ}{pvC}+S\cos\theta\Big)$$

$$+p\Big(\frac{-\alpha vQ}{pvC}+S\sin\theta\Big)\Big]\cos\Big(pt+\frac{px}{v}\Big)\Big]\Big\}$$

rearranging and simplifying terms:

$$2I=\varepsilon^{-\alpha x}\Big\{-Q\sin\Big(pt-\frac{px}{v}\Big)+S\frac{pvC}{p^2+\alpha^2v^2}\Big[(p\cos\theta$$

$$-\alpha v\sin\theta)\sin\Big(pt-\frac{px}{v}\Big)+(\alpha v\cos\theta+p\sin\theta)\Big]\Big\}$$

$$\times\cos\Big(pt-\frac{px}{v}\Big)$$

$$+\varepsilon^{\alpha x}\Big\{-Q\sin\Big(pt+\frac{px}{v}\Big)+S\frac{pvC}{p^2+\alpha^2v^2}\Big[(-p\cos\theta$$

$$+\alpha v\sin\theta)\ \sin pt+\frac{px}{v}\Big)-(\alpha v\cos\theta+p\sin\theta)\cos\Big(pt+\frac{px}{v}\Big)\Big]\Big\}$$

$$2I=\varepsilon^{-\alpha x}\Big\{-Q\sin\Big(pt-\frac{px}{v}\Big)+S\frac{pvC}{\sqrt{p^2+\alpha^2v^2}}$$

$$\times\Big[-\sin\Big(\theta-\tan^{-1}\frac{p}{\alpha v}\Big)\sin\Big(pt-\frac{px}{v}\Big)$$

$$+\cos\Big(\theta-\tan^{-1}\frac{p}{\alpha v}\Big)\cos\Big(pt-\frac{px}{v}\Big)\Big]\Big\}$$

$$+\varepsilon^{\alpha x}\Big\{-Q\sin\Big(pt+\frac{px}{v}\Big)+S\frac{pvC}{\sqrt{p^2+\alpha^2v^2}}$$

$$\times\left[\sin\left(\theta-\tan^{-1}\frac{p}{\alpha v}\right)\sin\left(p\,t+\frac{p\,x}{v}\right)-\cos\left(\theta-\tan^{-1}\frac{p}{\alpha v}\right)\right.$$

$$\left.\cos\left(p\,t+\frac{p\,x}{v}\right)\right]\Bigg\}$$

$$-2\,I=\varepsilon^{-\alpha x}\left\{Q\sin\left(p\,t-\frac{p\,x}{v}\right)-S\sqrt{\frac{p\,C}{\sqrt{R^2+p^2\,L^2}}}\right.$$

$$\left.\times\cos\left(p\,t+\theta-\frac{p\,x}{v}-\tan^{-1}\frac{p}{\alpha v}\right)\right\}$$

$$+\varepsilon^{\alpha x}\left\{Q\sin\left(p\,t+\frac{p\,x}{v}\right)+S\sqrt{\frac{p\,C}{\sqrt{R^2+p^2\,L^2}}}\right.$$

$$\left.\times\cos\left(p\,t+\theta+\frac{p\,x}{v}-\tan^{-1}\frac{p}{\alpha v}\right)\right\} \qquad (28)$$

since as already shown

$$\frac{p\,v\,C}{\sqrt{p^2+\alpha^2\,v^2}}=\sqrt{\frac{p\,C}{\sqrt{R^2+p^2\,L^2}}}$$

This equation shows the current at any point of the line for which equation (26) shows the voltage.

This equation can be put into a form similar to equation (27) by expanding the sine and cosine terms as before.

Thus,

$$-I=\frac{\varepsilon^{\alpha x}+\varepsilon^{-\alpha x}}{2}\left[Q\sin p\,t\cos\frac{p\,x}{v}-S\sqrt{\frac{p\,C}{\sqrt{R^2+p^2\,L^2}}}\right.$$

$$\left.\times\sin\left(p\,t+\theta-\tan^{-1}\frac{p}{\alpha v}\right)\sin\frac{p\,x}{v}\right]$$

$$+\frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2}\left[Q\cos p\,t\sin\frac{p\,x}{v}+S\sqrt{\frac{p\,C}{\sqrt{R^2+p^2\,L^2}}}\right.$$

$$\left.\times\cos\left(p\,t+\theta-\tan^{-1}\frac{p}{\alpha v}\right)\cos\frac{p\,x}{v}\right] \qquad (29)$$

The current is negative in equations (28) and (29), since when the potential rises in the positive direction from the origin, the current is in the opposite direction toward the origin.

The equations (27) and (29) give a second form of the exact equations (26) and (28) for the voltage and current at any point along a line when the current and voltage delivered by the line at the origin are

$Q \sin p\,t$ and $S \sin (p\,t+\theta)$ respectively.

SPECIAL CASES

These values should hold for the special cases where C, or L or $R = O$.

First case.

If $C = 0$,

$$\alpha = 0, \quad \frac{p\,x}{v} = x\sqrt{\frac{pC}{2}\left(p\,L+\sqrt{R^2+p^2\,L^2}\right)} = 0,$$

$$\frac{p}{\alpha\,v} = \frac{p\,L+\sqrt{R^2+p^2\,L^2}}{R}$$

and equation (27) becomes.

$$V = Q\sqrt{\sqrt{R^2+p^2\,L^2}}\left[\sin\left(p\,t+\tan^{-1}\frac{p}{\alpha\,v}\right)\left\{\frac{\sin\frac{px}{v}}{\sqrt{pC}}\right\}\right.$$

$$\left.-\cos\left(p\,t+\tan^{-1}\frac{p}{\alpha\,v}\right)\left(\frac{\frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2}}{\sqrt{p\,C}}\right)\right]+S\sin\,(p\,t+\theta)$$

But the expressions $\dfrac{\sin\frac{p\,x}{v}}{\sqrt{p\,C}}$ and $\dfrac{\frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2}}{\sqrt{p\,C}}$ both become $\dfrac{0}{0}$ when $C = 0$ and hence are indeterminate. As $\sin\dfrac{p\,x}{v}$ becomes 0, it equals $\dfrac{p\,x}{v}$. Thus substituting for, $\sin\dfrac{p\,x}{v}$, its value in the limit, $\dfrac{p\,x}{v}$,

$$\frac{\sin\frac{p\,x}{v}}{\sqrt{p\,C}} = \frac{\frac{p\,x}{v}}{\sqrt{p\,C}} = x\sqrt{\frac{p\,L+\sqrt{R^2+p^2\,L^2}}{2}}$$ which is determinate.

The expression

$$\frac{\frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2}}{\sqrt{p\,C}}$$

may be evaluated by differentiating numerator and denominator with regard to C and again putting $C = 0$.

Then

$$\frac{\frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2}}{\sqrt{p\,C}} = \frac{\frac{R\,x}{2}\sqrt{\frac{2\,p}{p\,L+\sqrt{R^2+p^2\,L^2}}}\left(\frac{1}{2}\sqrt{\frac{1}{C}}\right)\left(\frac{\varepsilon^{\alpha x}+\varepsilon^{-\alpha x}}{2}\right)}{\frac{1}{2}\sqrt{p}\sqrt{\frac{1}{C}}}$$

$$= Rx\sqrt{\frac{1}{2\,(p\,L+\sqrt{R^2+p^2\,L^2}}}$$

Therefore

$$V = x\,Q\sqrt{\sqrt{R^2+p^2\,L^2}}\left[\sqrt{\frac{p\,L+\sqrt{R^2+p^2\,L^2}}{2}}\sin\left(p\,t+\tan^{-1}\frac{p}{\alpha v}\right)\right.$$

$$\left.-R\sqrt{\frac{1}{2\,(p\,L+\sqrt{R^2+p^2 L^2})}}\cos\left(p\,t+\tan^{-1}\frac{p}{\alpha\,v}\right)\right]$$

$$+S\sin\,(p\,t+\theta)$$

combining sine and cosine terms

$$V = x\,Q\sqrt{\sqrt{R^2+p^2\,L^2}}$$

$$\times\sqrt{\left(\sqrt{\frac{p\,L+\sqrt{R^2+p^2\,L^2}}{2}}\right)^2+\left(R\sqrt{\frac{1}{2\,(p\,L+\sqrt{R^2+p^2\,L^2}}}\right)^2}$$

$$\sin\left(p\,t+\tan^{-1}\,\frac{p}{\alpha\,v}-\tan^{-1}\,\frac{R}{p\,L+\sqrt{R^2+p^2\,L^2}}\right)+S\sin\,(p\,t+\theta)$$

The two radicals forming the coefficient of the *sine* combined

$$=\sqrt{\sqrt{R^2+p^2\,L^2}}\sqrt{\frac{p\,L+\sqrt{R^2+p^2\,L^2}}{2}+\frac{R^2}{2(p\,L+\sqrt{R^2+p^2\,L^2})}}$$

$$=\sqrt{\sqrt{R^2+p^2\,L^2}}\sqrt{\frac{2\,(p^2\,L^2+R^2+p\,L\sqrt{R^2+p^2\,L^2})}{2\,(p\,L+\sqrt{R^2+p^2\,L^2})}}$$

$$=\sqrt{\sqrt{R^2+p^2\,L^2}}\sqrt{\sqrt{R^2+p^2\,L^2}} = \sqrt{R^2+p^2\,L^2}$$

The tangent of the difference of the two angles $\tan^{-\prime} p/\alpha v$ and

$$\tan^{-\prime} \frac{R}{p L+\sqrt{R^2+p^2 L^2}}$$

$$= \tan^{-\prime} \frac{\dfrac{p L+\sqrt{R^2+p^2 L^2}}{R} - \dfrac{R}{p L+\sqrt{R^2+p^2 L^2}}}{1+\dfrac{p L+\sqrt{R^2+p^2 L^2}}{R} \; \dfrac{R}{p L+\sqrt{R^2+p^2 L^2}}}$$

$$= \tan^{-\prime} \frac{\dfrac{2 p^2 L^2+2 p L\sqrt{R^2+p^2 L^2}}{R\,(p L+\sqrt{R^2+p^2 L^2})}}{2} = \tan^{-\prime} \frac{p L}{R}$$

Therefore,

$$V = x Q \sqrt{R^2+p^2 L^2} \sin \left(p\, t+\tan^{-\prime} \frac{p L}{R}\right)+S \sin\, (p\, t+\theta) \qquad (30)$$

where $x \sqrt{R^2+p^2 L^2}$ is the total impedance of the line.

This is seen to be the usual voltage formula for an inductive current.

With $C = 0$, from equation (29),

$$I = -Q \sin p\, t, \qquad (31)$$

as must be the case since, in the absence of capacity, no loss or gain of current can occur along the conductor.

Second case.

If $L = 0$, $\dfrac{p\, x}{v} = x\sqrt{\dfrac{p R C}{2}}$, $\alpha = \sqrt{\dfrac{p R C}{2}}$, $\dfrac{p}{\alpha v} = 1$

Equation (27) becomes

$$V = \frac{\varepsilon^{x\sqrt{(pRC)\div 2}}+\varepsilon^{-x\sqrt{(pRC)\div 2}}}{2}\left[Q\sqrt{\frac{R}{p\, C}} \sin\left(p t+\frac{\pi}{4}\right)\sin x\sqrt{\frac{p R C}{2}}\right.$$
$$\left. +S \sin\, (p\, t+\theta) \cos x\sqrt{\frac{p R C}{2}}\right]$$
$$+\frac{\varepsilon^{x\sqrt{(pRC)\div 2}}-\varepsilon^{-x\sqrt{(pRC)\div 2}}}{2}\left[-Q\sqrt{\frac{R}{p C}} \sin\left(p\, t+\frac{\pi}{4}\right)\right.$$
$$\left. \times \cos x\sqrt{\frac{p R C}{2}}+S \cos\, (p\, t+\theta) \sin x \sqrt{\frac{p R C}{2}}\right] \qquad (32)$$

Equation (29) becomes

$$-I = \frac{\varepsilon^{x\sqrt{(pRC)\div 2}} + \varepsilon^{-x\sqrt{(pRC)\div 2}}}{2}\Big[Q \sin p\,t \cos x\sqrt{\frac{p\,R\,C}{2}}$$

$$-S\sqrt{\frac{p\,C}{R}}\ \sin\left(p\,t+\theta-\frac{\pi}{4}\right)\sin x\sqrt{\frac{p\,R\,C}{2}}\Big]$$

$$+\frac{\varepsilon^{x\sqrt{(pRC)\div 2}} - \varepsilon^{-x\sqrt{(pRC)\div 2}}}{2}\Big[Q \cos p\,t \sin x\sqrt{\frac{p\,R\,C}{2}}$$

$$+S\sqrt{\frac{p\,C}{R}}\ \cos\left(p\,t+\theta-\frac{\pi}{4}\right)\cos x\sqrt{\frac{p\,R\,C}{2}}\Big] \qquad (33)$$

Third case.

If $R = 0$,

$$\frac{p\,x}{v} = x\sqrt{p^2 L\,C},\ \frac{p}{\alpha\,v} = \infty,\ \alpha = 0$$

Equation (27) becomes

$$V = Q\sqrt{\frac{L}{C}}\cos p\,t \sin x\sqrt{p^2 L C} + S\sin(p\,t+\theta)\cos x\sqrt{p^2 L\,C} \quad (34)$$

Equation (29) becomes

$$-I = Q\sin p\,t\cos x\sqrt{p^2 L\,C} + S\sqrt{\frac{C}{L}}\cos(p\,t+\theta)\sin x\sqrt{p^2 L C} \qquad (35)$$

Other cases. If $R = 0$ as well as C from equation (30) [or if $C = 0$ as well as R in equation (34)]

$$V = p\,L\,x\,Q\cos p\,t + S\sin(p\,t+\theta)$$

where $x\,p\,l$ = total inductance of the line.

If $L = 0$ as well as C from equation (30)

$$V = x\,R\,Q\sin p\,t + S\sin(p\,t+\theta)$$

where $x\,R$ is the total resistance of the line.

If $L = 0$ as well as R in equation (34),

$$V = S \sin (p\,t + \theta)$$

and from equation (35)

$$-I = Q \sin p\,t + S\sqrt{C} \cos (p\,t + \theta) \left(\frac{\sin x \sqrt{p^2 L C}}{\sqrt{L}}\right)$$

The expression $\dfrac{\sin x \sqrt{p^2 L C}}{\sqrt{L}} = \dfrac{0}{0}$. As before in the limit

$\sin x \sqrt{p^2 L C} = x \sqrt{p^2 L C}$

therefore

$$-I = +Q \sin p\,t + p\,C\,x\,S \cos (p\,t + \theta)$$

This is the well-known formula for a shunt condenser, where $C\,x$ = total capacity of the line.

Thus in the various special cases where the quantities, voltage and current cease to be wave functions, the general equations reduce to the well-known forms, but in each case the change from the wave function to the simple function is through the evaluation of an indeterminate form.

As long as the line contains capacity, and either resistance or inductance, these functions are in wave form, as they include trigonometrical functions of angles including the distance x from the origin. In other cases the formulas represent the algebraic form of function.

PHYSICAL MEANING OF EQUATIONS

Equations (26) and (28) give perhaps the best idea of the physical nature of the phenomenon of voltage and current variation. As a matter of fact there exists only a single resultant succession of waves passing in the line. It is helpful sometimes, however, to consider that the resultant wave is made up of a number of component waves.

Suppose, for example, that a perfectly uncharged line be connected to a source of sine electromotive force. A wave will pass into the line and will lose a little of its energy or amplitude as it passes along, and at the end will be reflected and pass backward along the line in the same manner, getting gradually less all the way. This wave reaching the generator will be absorbed, while the generator continues to send out similar waves.

Considering now the receiving end where the potential waves are reflected and the neighborhood of this point, there are at all times two component potential waves at each point in the line, one going toward the reflecting point and the other coming from it. These waves remain the same as they travel, except for decrease in amplitude due to the resistance losses, and for their phase which is, of course, further advanced in the time angle and less advanced by the space angle in the leading wave. The reflected potential wave is represented by the term

$$S \sin \left(p\,t - \frac{p\,x}{v} + \theta\right)$$

and the direct wave by the expression

$$S \sin \left(p\,t + \frac{p\,x}{v} + \theta\right)$$

the angle $\frac{p\,x}{v}$ being the part of a cycle $(2\,\pi)$ occupied by the wave in passing over the distance x to or from the point of reflection. But the current produces a drop in the line, proportional to the current and square root of the impedance, and inversely proportional to the square root of the capacity susceptance, as is shown by the equation(26). The current wave passes along together with the potential wave toward the reflecting point, being represented by the expression

$$Q \sin \left(p\,t + \frac{p\,x}{v}\right)$$

Similarly with the reflected current wave

$$Q \sin \left(p\,t - \frac{p\,x}{v}\right)$$

which passes back through the line from the reflecting point. But the potential due to the current wave is not in phase with the current but occurs earlier than the current by the angle

$$\tan^{-1} \frac{p}{\alpha\,v} = \tan^{-1} \frac{p\,L + \sqrt{R^2 + p^2\,L^2}}{R}$$

Again the direction of the drop in line, produced by the current wave after reflection, is opposite with regard to the voltage from that due to the direct current wave. This appears in the equation by the positive sign of the quantity

$$+Q\sqrt{\frac{\sqrt{R^2+p^2L^2}}{pC}}\cos\left(pt-\frac{px}{v}+\tan^{-1}\frac{p}{\alpha v}\right),$$ representing

the reflected wave.

Thus the total resultant voltage is the combination of these four quantities, the direct and reflected potential waves, which decrease as they travel, as indicated by the two factors: first,

$$e^{\alpha x},$$

indicating that the direct wave is greater than the value at the reflecting point, since it will decrease somewhat by travelling along the line to the reflecting point; and, second, by the factor

$$e^{-\alpha x},$$

indicating that the reflected wave is less than the value at the reflecting point, since it has passed along the line some distance from this point, and the direct and reflected current wave drops.

Since Q and S, however, should be the total delivered current and voltage but momentarily taken for the maximum value of each wave, the sum of the four waves will be twice the actual voltage, as is shown by the equation (26).

Similarly with the current formula (28) where the resultant current is made up of four elements, the direct and reflected current waves which diminish as they travel at the rate $e^{\alpha x}$, and a direct and reflected curve due to the effect of the voltage wave and consisting of charging current. The direct-current wave, due to the direct-voltage wave, is represented by the expression

$$S\sqrt{\frac{pC}{\sqrt{R^2+p^2L^2}}}\sin\left(pt+\frac{px}{v}+\theta-\tan^{-1}\frac{p}{\alpha v}\right)$$

The phase angle here shown is due partly to the ordinary time variation (pt), partly to the distance it has to pass to reach the reflecting point $\frac{px}{v}$, partly to the lead of the delivered voltage over the current (θ) and partly due to the lag between the charging current wave and the voltage wave causing it, $\tan^{-1} \frac{p}{\alpha v}$

Similarly with the phase of the corresponding reflected wave, in which, however, the wave has passed the reflecting point and is thus earlier than the waves at that point by the angle $\frac{p x}{v}$.*

Again it will be noticed that while the component current waves are sine quantities, the charging-current waves produced by the voltage waves appear as cosine quantities. This is because the charging current is primarily proportional to the rate of change of voltage and not directly to the voltage. The cosine, of course, gives the rate of change of the sine.

NUMERICAL CALCULATIONS BY WAVE FORMULA

Numerical calculations. For purposes of numerical calculation these equations can be considerably simplified. Starting with equation (27) the voltage is seen to be the summation of four terms, sines and cosines, having varying phase relations. The simplest way to determine the maximum value of the resultant wave, numerically in a given case, is to substitute in the equation separately two values of $p t$, 90 degrees apart, and the square root of the sum of the squares of the results of these substitutions will be the resultant maximum. In this case $p t$ will be put $= 0$ and then $= \pi/2$.

Then equation (27) gives for $p t = 0$

$$V_0 = \left[S \sin\theta \cos \frac{p x}{v} + Q \sqrt{\frac{\sqrt{R^2 + p^2 L^2}}{p C}} \sin \tan^{-1} \frac{p}{\alpha v} \right.$$

$$\left. \times \sin \frac{p x}{v} \right] \frac{\varepsilon^{\alpha x} + \varepsilon^{-\alpha x}}{2} + \left[S \cos\theta \sin \frac{p x}{v} - Q \sqrt{\frac{\sqrt{R^2 + p^2 L^2}}{p C}} \right.$$

$$\left. \times \cos \tan^{-1} \frac{p}{\alpha v} \cos \frac{p x}{v} \right] \frac{\varepsilon^{\alpha x} - \varepsilon^{-\alpha x}}{2} \qquad (36)$$

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* In this connection, attention is called to the writer's paper before the A. I. E. E. of February, 1902, TRANSACTIONS, Vol. xiv, p. 213, where a somewhat similar, non-mathematical, description of electric waves is given. The equations here derived conform exactly to the principles there laid down.

For $p\,t = \frac{\pi}{2}$

$$\begin{aligned} V_{\frac{\pi}{2}} = & \left[S \cos\theta \cos\frac{p\,x}{v} + Q \sqrt{\frac{\sqrt{R^2+p^2L^2}}{p\,C}} \cos\tan^{-1}\frac{p}{\alpha\,v} \right. \\ & \left. \times \sin\frac{p\,x}{v} \right] \frac{\varepsilon^{\alpha x}+\varepsilon^{-\alpha x}}{2} + \left[-S \sin\theta \sin\frac{p\,x}{v} \right. \\ & \left. + Q \sqrt{\frac{\sqrt{R^2+p^2L^2}}{p\,C}} \sin\tan^{-1}\frac{p}{\alpha\,v} \cos\frac{p\,x}{v} \right] \frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2} \end{aligned} \qquad (37)$$

Similarly, with equation (29) putting $p\,t = 0$

$$\begin{aligned} -I_0 = & \left[0 + S \sqrt{\frac{p\,C}{\sqrt{R^2+p^2L^2}}} \left(-\sin\left(\theta - \tan^{-1}\frac{p}{\alpha\,v}\right) \right. \right. \\ & \left. \left. \times \sin\frac{p\,x}{v} \right) \right] \frac{\varepsilon^{\alpha x}+\varepsilon^{-\alpha x}}{2} + \left[Q \sin\frac{p\,x}{v} + S \sqrt{\frac{p\,C}{\sqrt{R^2+p^2L^2}}} \right. \\ & \left. \times \left(\cos\left(\theta - \tan^{-1}\frac{p}{\alpha\,v}\right) \cos\frac{p\,x}{v} \right) \right] \frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2} \end{aligned} \qquad (38)$$

putting $p\,t = \frac{\pi}{2}$

$$\begin{aligned} -I_{\frac{\pi}{2}} = & \left[Q \sin\frac{p\,x}{v} + S \sqrt{\frac{p\,C}{\sqrt{R^2+p^2L^2}}} \left(-\cos\left(\theta - \tan^{-1}\frac{p}{\alpha\,v}\right) \right. \right. \\ & \left. \left. \times \sin\frac{p\,x}{v} \right) \right] \frac{\varepsilon^{\alpha x}+\varepsilon^{-\alpha x}}{2} + \left[0 + S \sqrt{\frac{p\,C}{\sqrt{R^2+p^2L^2}}} \right. \\ & \left. \times \left(-\sin\left(\theta - \tan\frac{p}{\alpha\,v}\right) \cos\frac{p\,x}{v} \right) \right] \frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2} \end{aligned} \qquad (39)$$

Rearranging terms and putting $\frac{\varepsilon^{\alpha x}+\varepsilon^{-\alpha x}}{2} = k_1$ and $\frac{\varepsilon^{\alpha x}-\varepsilon^{-\alpha x}}{2} = k_2$, and dropping the negative signs before I_0 and $I_{\frac{\pi}{2}}$ as having no significance in the numerical computations, we have the following :

FORMULAS FOR NUMERICAL CALCULATIONS.

$$V_0 = S\left(\left(k_1 \cos\frac{px}{v}\right)\sin\theta + \left(k_2 \sin\frac{px}{v}\right)\cos\theta\right) + Q\sqrt{\frac{\sqrt{R^2+p^2L^2}}{pC}}\left(\left(k_1 \sin\frac{px}{v}\right)\sin\tan^{-1}\frac{p}{\alpha v} - \left(k_2\cos\frac{px}{v}\right)\cos\tan^{-1}\frac{p}{\alpha v}\right) \quad (40)$$

$$V_{\substack{x\\y}} = S\left(\left(\text{“} \quad \text{“}\right)\cos\theta - \left(\text{“} \quad \text{“}\right)\sin\theta\right) + Q\sqrt{\frac{\sqrt{R^2+p^2L^2}}{pC}}\left(\left(\text{“} \quad \text{“}\right)\cos\tan^{-1}\frac{p}{\alpha v} + \left(\text{“} \quad \text{“}\right)\sin\tan^{-1}\frac{p}{\alpha v}\right) \quad (41)$$

$$I_0 = \qquad + \left(\text{“} \quad \text{“}\right)Q + S\sqrt{\frac{pC}{\sqrt{R^2+p^2L^2}}}\left(\left(\text{“} \quad \text{“}\right)\sin\left(\tan^{-1}\frac{p}{\alpha v}-\theta\right) + \left(\text{“} \quad \text{“}\right)\cos\left(\tan^{-1}\frac{p}{\alpha v}-\theta\right)\right) \quad (42)$$

$$I_{\substack{x\\y}} = \left(\text{“} \quad \text{“}\right)Q \qquad - S\sqrt{\frac{pC}{\sqrt{R^2+p^2L^2}}}\left(\left(\text{“} \quad \text{“}\right)\cos\left(\tan^{-1}\frac{p}{\alpha v}-\theta\right) - \left(\text{“} \quad \text{“}\right)\sin\left(\tan^{-1}\frac{p}{\alpha v}-\theta\right)\right) \quad (43)$$

Note, as determined below :

$$V = \sqrt{V_0^2 + V_{\substack{x\\y}}^2} = V_0 + \sin\tan^{-1}\frac{V_0}{V_{\substack{x\\y}}} = V_{\substack{x\\y}} + \cos\tan^{-1}\frac{V_0}{V_{\substack{x\\y}}};\ I = \sqrt{I_0^2 + I_{\substack{x\\y}}^2} = I_0 + \sin\tan^{-1}\frac{I_0}{I_{\substack{x\\y}}} = I_{\substack{x\\y}} + \cos\tan^{-1}\frac{I_0}{I_{\substack{x\\y}}}$$

Generator power-factor $= \cos\left(\tan^{-1}\frac{V_0}{V_{\substack{x\\y}}} - \tan^{-1}\frac{I_0}{I_{\substack{x\\y}}}\right)$, line energy loss $= V\,I$ (gen. P. F.) $- S\,Q\cos\theta$

$k_1 = 1 + \frac{\alpha^2 x^2}{2}$, $k_2 = \alpha x\left(1 + \frac{\alpha^2 x^2}{6}\right)$, load voltage $= S$, load current $= Q$, load power-factor $= \cos\theta$

Then

$$V = \sqrt{V_0^2 + V_{\frac{\pi}{2}}^2}, \quad I = \sqrt{I_0^2 + I_{\frac{\pi}{2}}^2}$$

These equations serve to give the calculation of generator current and voltage in actual cases. It is more convenient instead of using the expressions $\sqrt{V_0^2 + V_{\frac{\pi}{2}}^2}$ and $\sqrt{I_0^2 + I_{\frac{\pi}{2}}^2}$ to consider the trigonometrical relations of the quantities V_0, $V_{\frac{\pi}{2}}$, I_0, and $I_{\frac{\pi}{2}}$, graphically in their triangles, in this case

$$V = V_0 \div \sin \tan^{-1} \frac{V_0}{V_{\frac{\pi}{2}}} \text{ and } I = I_0 \div \sin \tan^{-1} \frac{I_0}{I_{\frac{\pi}{2}}} \quad (44) \quad (45)$$

The phase angle by which the current lags behind the voltage at the generator is the difference in the phase angles of the two resultant quantities just determined, namely, the angles, $\tan^{-1} \frac{V_0}{V_{\frac{\pi}{2}}}$ and $\tan^{-1} \frac{I_0}{I_{\frac{\pi}{2}}}$. The power-factor of the generator power is the cosine of this angle

$$\cos\left(\tan^{-1} \frac{V_0}{V_{\frac{\pi}{2}}} - \tan^{-1} \frac{I_0}{I_{\frac{\pi}{2}}}\right)$$

The generator conditions are thus completely determined.

In making calculations it should be noted that

$$\frac{\varepsilon^{\alpha x} + \varepsilon^{-\alpha x}}{2} = k_1 = 1 + \frac{\alpha^2 x^2}{1.2.3} + \frac{\alpha^4 x^4}{1.2.3.4} + \ldots$$

and that

$$\frac{\varepsilon^{\alpha x} - \varepsilon^{-\alpha x}}{2} = k_2 = \alpha x + \frac{\alpha^3 x^3}{1.2.3} + \frac{\alpha^5 x^5}{1.2.3.4.5} + \ldots$$

Two terms of these series are always accurate enough for numerical calculations.

$\sqrt{R^2 + p^2 L^2}$ is of course the impedance per unit length of line. Any convenient unit of length may be taken provided it is used throughout.

In actual calculations the following procedure is recommended:

Having given:

Length line, 700 miles.
Size conductors, 3 No. 0000.
Spacing wires, 12 foot triangle.
Power delivered, 40,000 three-phase, 20,000 in single phase for equivalent drop.
Voltage delivered 150,000.
Power-factor of delivered power, .918.
Current delivered, 145, single phase.

Take from tables:

Resistance of line per loop unit length = $R = 0.17$ ohms.
Inductive ohms $= p\,L$ (L in henrys) $= 2\,\pi\,n\,L = 0.619$ ohms.
Impedance ohms $= \sqrt{R^2 + p^2\,L^2} =$ .... 0.643 ohms.
Capacity susceptance $= p\,C = 2\,\pi\,n\,C$
= charging current per volt (capacity must be in farads,
= capacity in microfarads $\div 10^6$) = ...000001193

By calculation,

Cos $\theta = 0.918$, $\theta = 23°, 20'$, sin $\theta = 0.400$.

$$\frac{p\,x}{v} = x\sqrt{\frac{p\,C\,(p\,L + \sqrt{R^2 + p^2 L^2})}{2}}$$

$$= x\sqrt{\frac{\text{cap. suscept. (induct. + imped.)}}{2}}$$

$$= 700\sqrt{\frac{0.000001193}{2}(0.619 + 0.643)} = 0.607$$

To get 0.607 into degrees multiply by $\frac{360}{2\,\pi}$

$$0.607 \times \frac{360}{2\,\pi} = 34°, 48'$$

$$\sin\frac{p\,x}{v} = 0.571, \cos\frac{p\,x}{v} = 0.821$$

$$\frac{p}{\alpha\,v} = \frac{p\,L + \sqrt{R^2 + p^2\,L^2}}{R} = \frac{0.619 + 0.643}{0.17} = 7.43$$

$$\tan^{-1} 7.43 = 82^\circ\ 20', \ \sin \tan^{-1} \frac{p}{\alpha v} = 0.991, \cos \tan^{-1} \frac{p}{\alpha v} = 0.133$$

$$\left(\tan^{-1} \frac{p}{\alpha v} - \theta\right) = 59^\circ.$$

$$\text{Sin} \left(\tan^{-1} \frac{p}{\alpha v} - \theta\right) = 0.857, \cos \left(\tan^{-1} \frac{p}{\alpha v} - \theta\right) = 0.515$$

$$\alpha x = \frac{R x}{2} \sqrt{\frac{2 p C}{p L + \sqrt{R^2 + p^2 L^2}}}$$

$$= \frac{700 \times 0.17}{2} \sqrt{\frac{2 \times .000001193}{0.619 + 0.643}} = 0.0819$$

$$\sqrt{\frac{p C}{\sqrt{R^2 + p^2 L^2}}} = \sqrt{\frac{.000001193}{0.643}} = 0.001364$$

$$k_1 = 1 + \frac{\alpha^2 x^2}{2} = 1.0033$$

$$k_2 = 0.082 \left(1 + \frac{\alpha^2 x^2}{6}\right) = 0.0819\ (1 + .0011) = 0.0820$$

$$k_1 \sin \frac{p x}{v} = 0.574 \qquad k_1 \cos \frac{p x}{v} = 0.825$$

$$k_2 \sin \frac{p x}{v} = 0.0468 \qquad k_2 \cos \frac{p x}{v} = 0.0673$$

These quantities can now be substituted in the equations 40-43, giving

$$V_0 = 150000\,[(0.825)\ (0.400) + (0.0468)\ (0.918)]$$

$$+ \frac{145}{0.001364} [(0.5735)\ (0.991) - (0.0673)\ (0.133)]$$

$$V_{\frac{x}{2}} = 150000\,[(0.825)\ (0.918) - (0.0468)\ (0.400)]$$

$$+ \frac{145}{0.001364} [(0.5735)\ (0.133) + (0.0673)\ (0.991)]$$

$$I_0 = 145\ (0.0468)$$

$$+150000 \times .001364\ [(0.5735)\ (0.857) + (0.0673)\ (0.515)]$$

$$I_{\frac{\pi}{2}} = 145\ (0.825)$$

$$-150000 \times 0.001364\ [(0.5735)\ (0.515) - (0.0673)\ (0.857)]$$

Then

$$V_0 = 150000\ (0.370) + 145\ (409) = 114{,}900$$

$$V_{\frac{\pi}{2}} = 150000\ (0.738) + 145\ (104.7) = 125{,}900$$

$$I_0 = 145\ (0.0468) + 150000\ (0.000719) = 114.6$$

$$I_{\frac{\pi}{2}} = 145\ (0.825) - 150000\ (0.000325) = 71.2$$

$$V = 125{,}900 \div \cos \tan^{-1} \frac{114{,}900}{125{,}900}$$

$$= 125{,}900 \div \cos\ (42°,\ 25') = 170{,}600$$

$$I = 114.6 \div \sin \tan^{-1} \frac{114.6}{71.2}$$

$$= 114.6 \div \sin\ (58°,\ 10') = 135.$$

$$\text{Generator power-factor} = \cos\ (42°,\ 25' - 58°,\ 10')$$

$$= \cos\ (-15°,\ 45') = 0.963.$$

Since the lag angle is negative the current is leading. The true power at the generator is $V\ I \times 0.963 = 22{,}320$ kw. The line energy loss is 2320 kw. = 10.7%

$$\text{The voltage drop is } \frac{170{,}600 - 150{,}000}{170{,}600} = 12.1\%.$$

Thus the conditions of the generator and line are all determined.

The sign of the various quantities making up V_0, $V_{\frac{\pi}{2}}$, I_0, $I_{\frac{\pi}{2}}$ must be carefully preserved to determine the generator power-factor properly; it should be noted that $\tan^{-1}\ (-x/y) = 180° - \tan^{-1} x/y$ and that $\cos\ (-x) = \cos x$, while $\sin\ (-x) = -\sin x$.

Once the calculation has been made on one particular line for one load, the recalculation for other loads and other voltages is very easy. If the power-factor of the load is the same, only the quantities S and Q need be changed in equations (40) (41) (42) and (43).

If the power-factor of the delivered load is changed, the angles containing θ are of course correspondingly changed, but this does not greatly lengthen the recalculations.

SPLIT-CAPACITY FORMULA

For purposes of comparison with the wave formula as here derived, the writer ventures to introduce an approximate formula for calculation of the line quantities, based on the assumption that one-half of the line capacity is concentrated at each end of the line.

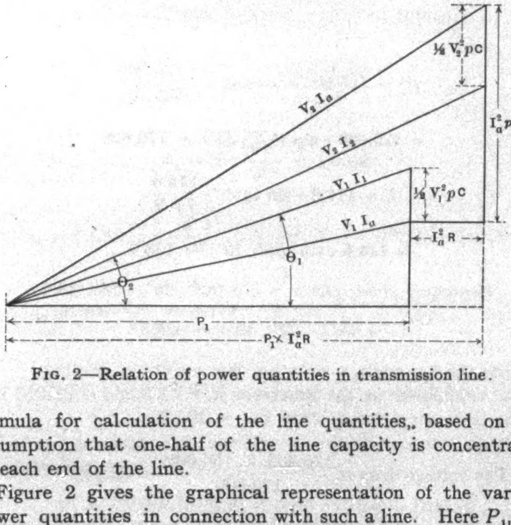

FIG. 2—Relation of power quantities in transmission line.

Figure 2 gives the graphical representation of the various power quantities in connection with such a line. Here P_1, V_1, $\cos \theta_1$ are the power, voltage, and power-factor of the delivered load. Let I_a be the current in the receiving end in the line itself, and

Let P_2, V_2, I_2, and $\cos \theta_2$ be the power, voltage, current and power-factor at the generator. The relations of the *power* quantities are shown in Fig. 2, and the following equations can be written down by inspection:—

$$V_1 I_a = P_1 \div \cos \tan^{-1} \frac{P_1 \tan \theta_1 - \frac{p C V_1^2}{2}}{P_1}$$

$$V_2 I_a = (P_1 + I_a^2 R) \div \cos \tan^{-1} \frac{P_1 \tan \theta_1 - \frac{p C V_1^2}{2} + I_a^2 pL}{P_1 + I_a^2 R}$$

$$V_2 I_2 = (P_1 + I_a^2 R) \div \cos \tan^{-1} \frac{P_1 \tan \theta_1 - \frac{p C V_1^2}{2} + I_a^2 pL - \frac{p C V_2^2}{2}}{P_1 + I_a^2 R}$$

These can be more conveniently written

$$I_a = \frac{P_1}{V_1} \div \cos \tan^{-1} \frac{P_1 \tan \theta_1 - \frac{p C V_1^2}{2}}{P_1} \qquad (46)$$

$$V_2 = \frac{P_1 + I_a^2 R}{I_a} \div \cos \tan^{-1} \frac{P_1 \tan \theta_1 - \frac{p C V_1^2}{2} + I_a^2 pL}{P^1 + I_a^2 R} \qquad (47)$$

$$I_2 = \frac{P_1 + I_a^2 R}{V_2} \div \cos \tan^{-1} \frac{P_1 \tan \theta_1 - \frac{p C V_1^2}{2} + I_a^2 pL - \frac{p C V_2^2}{2}}{P_1 + I_a^2 R}$$

$$= \frac{P_1 + I_a^2 R}{V_2} \div \cos \theta_2 \qquad (48)$$

Generator power factor =

$$\cos \theta_2 = \cos \tan^{-1} \frac{P_1 \tan \theta_1 - \frac{p C V_1^2}{2} + I_a^2 pL - \frac{p C V_2^2}{2}}{P_1 + I_a^2 R}$$

These equations are well suited to numerical calculations, especially when several sections of line carrying different loads and having different constants are fed in series.

The difference between the mathematical forms of the wave formula and the split-capacity formula is marked, and it becomes important to know how much difference there may be in the numerical results shown by the two formulas. For purposes of comparison, a considerable number of cases, including some of those calculated by the wave formula in the companion paper, have been calculated by both formulas and the results tabulated in Table I.

Here it is seen that for ordinary commercial cases up to perhaps 150 miles (as cases *A*, *B*, *C*, *D*, *R*, and *S* in Table I) there is only a few tenths of one per cent difference in the results of the two formulas, but that with very long lines the error may reach several per cent in voltage drop, as in (*I*, *K*, *L*, *M*, *P*, *Q*, *T*, *U*, *V*, and *W* of table I).

The error may occur in voltage, energy loss, current or power-factor and may be either positive or negative.

Cases *R* and *S*, Table I are of a lead-covered cable of assumed constants; here the discrepancy between the formulas is very small, even though this is an extreme case for a cable transmission. Strictly speaking in this case the leakage of current through the insulation should be considered. The effect of this leakage would here be negligible, however.

It is interesting to note that the line may act to a limited extent as a raising transformer in those cases where the capacity is relatively important. That is, energy given to the line at one voltage may be delivered to the load at a lower voltage and larger current. For example, in cases *C*, *P*, and *T*, the total generator current is less than the power component of the load current. In view, however, of the higher generator voltage the *energy* represented by the generator current is greater than that represented by the load current, the excess being the energy line loss.

In applying the split-capacity formula to the case where the load is 0 and only charging current flows, the expression for I_a becomes indeterminate. In this case, however, I_a = the charging current of one-half the line capacity and the formula for I_a need not be used. The rest of the formula does not become indeterminate.

In applying the split-capacity formula to cases where leading current is taken by a synchronous machine at the load end of the line, it must be noted that while this current is leading in the machine it is lagging in the line,—measuring toward the load—and thus has the same effect as lagging load current. With such machines taking leading current, their apparent power is introduced in the formula as part or the whole of the quantity, $P_1 \tan \theta_1$, with the positive sign.

These formulas are all adapted to single-phase calculations. Three-phase lines may be calculated by the well-known rule, that the energy line loss, voltage drop, and power-factor expressed *in percentage* are the same, including effect of capacity current, for a three-phase system as for a single-phase system transmitting one-half the power over any pair of the three-phase wires, which are assumed to be arranged in the usual equilateral triangle grouping. The correctness of this rule is easily seen. With two parallel wires carrying currents, the ohmic drop is the resultant of the drops in the two wires; the inductive e.m.f. depends upon the total number of lines of force between the wires, which will be due to the resultant of the magnetism due to the currents in the two wires individually and the capacity depends upon the potential between wires necessary to produce a given charge on the wires. This potential may be measured by carrying a unit positive charge of electricity from one wire to the other and determining the work done in virtue of the two charges on the two wires. It should be noted that the third wire of a three-phase system, in virtue of its symmetrical position, has no effect either on the lines of force passing between the other two wires, nor upon the total work done in moving a charge between them.

In each of the above cases when the wires carry single-phase currents the effects of the two wires are 180 degrees apart in phase, but are additive in the summation giving the total ohmic and inductive electromotive force and the work done by a positive charge is equal to double that from one wire only.

With three-phase, on the other hand, the two wires have their effects 120 degrees apart instead of 180 degrees so that the resultant effects are not twice but $\sqrt{3}$ times the effect of one wire. So the ratio $\frac{2}{\sqrt{3}}$ exists between these quantities when the wires carry the same current three-phase and single-phase. To have the same ohmic and inductive e.m.f., which depend upon the current, whether the wires carry single-phase or three-phase current, the single-phase current must be reduced in the ratio $\frac{2}{\sqrt{3}}$, reducing the single-phase power by this amount. But in virtue of the third wire of the three-phase system, it carries $\sqrt{3}$ times as much power as the single-phase having the same current. Therefore, the ratio $\frac{2}{\sqrt{3}} \times \sqrt{3} = 2$ gives the ratio of the power in a single-phase circuit and a three-phase circuit, when in the single-phase circuit and in any two wires of the three-phase circuit, there exists the same resultant ohmic drop total and the same resultant inductive e.m.f. In this case the actual line current in the case of the three-phase will be $\frac{2}{\sqrt{3}}$ times that of the single-phase.

Since the work done by the positive charge in passing between the two wires of the three-phase is only $\frac{\sqrt{3}}{2}$ times that in the single-phase case, the capacity and charging current must be $\frac{2}{\sqrt{3}}$ greater in the three-phase case. Thus the ratio of charging currents in the two circuits is the same as that of the load currents, and the power-factor relations, as well as the voltage relations, must remain the same in the two circuits. Thus the true energy loss in per cent must be the same in the two cases, as already stated.

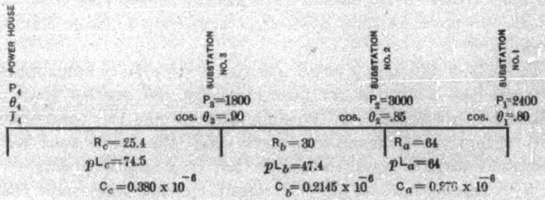
POWER HOUSE
P_4
θ_4
I_4
SUBSTATION NO. 3
$P_3=1800$
cos. $\theta_3=.90$
SUBSTATION NO. 2
$P_2=3000$
cos. $\theta_2=.85$
SUBSTATION NO. 1
$P_1=2400$
cos. $\theta_1=.80$
$R_c=25.4$
$pL_c=74.5$
$C_c=0.380 \times 10^{-6}$
$R_b=30$
$pL_b=47.4$
$C_b=0.2145 \times 10^{-6}$
$R_a=64$
$pL_a=64$
$C_a=0.276 \times 10^{-6}$

FIG. 3—Distribution of loads and line constants in assumed transmission line

This conclusion can be reached by algebraic and trigonometrical methods, but the above demonstration is much simpler and its logic is believed to be sound.

The split-capacity formula is especially convenient where on account of intermediate substations several sections of the line have different constants and different loads; in this case if only the generator quantities are required the calculation can be made as follows: Let there be three stations along a line each receiving power, and let the different sections of the line have different constants all as indicated in Fig. 3. Calculations are made for single-phase, assuming half the power transmitted.

Delivered voltage 60,000, 60 cycles	True power quantities	Wattless quantities
Power at substation 1	1,200,000	
Wattless component $P_1 \tan \theta_1$		+905,000
Capacity energy at 1, $\frac{p C_a V_1^2}{2}$		− 187,000
	1,200,000	718,000
$I_a = \frac{P_1}{V_1} \div \cos \tan^{-1} \frac{718{,}000}{1{,}200{,}000} = 23.3$		
$I_a^2 R_a =$	35,000	
$I_a^2 p L_a =$		35,000
	1,235,000	753,000
$V_2 = \frac{1{,}235{,}000}{23.3} \div \cos \tan^{-1} \frac{753{,}000}{1{,}235{,}000}$		
$= 62{,}000$		
Capacity energy at 2, $V_2^2 \left(\frac{p C_a}{2} + \frac{p C_b}{2}\right) =$		− 356,000
Power at substation 2	1,500,000	
Wattless at substation 2, $(P_2 \tan \theta_2)$		+930,000
	2,735,000	1,327,000
$I_b = \frac{2{,}735{,}000}{62{,}000} \div \cos \tan^{-1} \frac{1{,}327{,}000}{2{,}735{,}000} = 49$		
$I^2_b R_b =$	72,000	
$I^2_b p L_b =$		114,000
	2,807,000	1,441,000
$V_3 = \frac{2{,}807{,}000}{49} \div \cos \tan^{-1} \frac{1{,}441{,}000}{2{,}807{,}000}$		
$= 64{,}400$		
Capacity energy at substation 3		
$= V_3^2 \left(\frac{p C_b}{2} + \frac{p C_a}{2}\right) =$		− 451,000
Power at substation 3 $= P_3$	900,000	
Wattless at substation 3 $= P_3 \tan \theta_3$....		+435,000
	3,707,000	1,425,000

$$I_c = \frac{3{,}707{,}000}{64{,}400} \div \cos\tan^{-1}\frac{1{,}425}{3{,}707} = 61.7$$

$I_c^2 R_c =$	96,500	
$I_c^2 pL_c =$		+283,000
	3,804,000	1,708,000

V_4 (at generator)

$$= \frac{3{,}804{,}000}{61.7} \div \cos\tan^{-1}\frac{1{,}708{,}000}{3{,}804{,}000}$$

$$= 67{,}600$$

Capacity energy at generator

$\frac{p\,C_c\,V_4^2}{2}$		− 327,000
	3,804,000	1,381,000

$$I_4 = \frac{3{,}804{,}000}{67{,}600} \div \cos\tan^{-1}\frac{1{,}381{,}000}{3{,}804{,}000}$$

$$= \frac{3{,}804{,}000}{67{,}600} \div \cos 20^\circ \qquad = \frac{3{,}804{,}000}{67{,}600} \div 0.94 = 59.8$$

$\cos\theta_4 =$ power factor $= 0.94$

For 3-phase at generator.

Power = 7610 kw., $K\,V\,A = 8100$, power factor = 0.94

Drop = 7,600 volts. Energy line loss = 410 kw.

INDUCTION FORMULAS FOR SPLIT CONDUCTORS

The use of split conductors to vary the ratio of capacity and inductance in a transmission line is discussed in the companion paper. An approximate formula for calculating the inductance of a line with split conductors will be derived. Assume a three-phase line of the usual form, but with each conductor split into three parts as shown in Fig. 4; the total inductance between one group of conductors and the neutral point will be determined and then compared with the usual formula for such total inductance, with a single conductor, placed at the center of gravity of the three, at the point Q_1 Fig. 4.

The total inductance sought will be the resultant of the inductances caused by the various currents of the system separately. It will first be proved that the total amount of induction between two points in space, perpendicular to the line joining these points, due to a long straight wire carrying a current I, is equal to $2 \log_e \frac{M}{N}$, where M and N are, respectively, the distances to the more remote and the nearer points. In Fig. 5 let I be the point where the current I passes through the plane of the paper and let S and U be the two points between which induction is to be measured. Let T be any point in the line between the points U and S at a distance x from the base O of a normal to the line $U\,S$ from I. The magnetic field at T is then $\frac{2\,I}{\sqrt{q^2+x^2}}$ when q is the length of the normal, and $\sqrt{q^2+x^2}$ is the distance

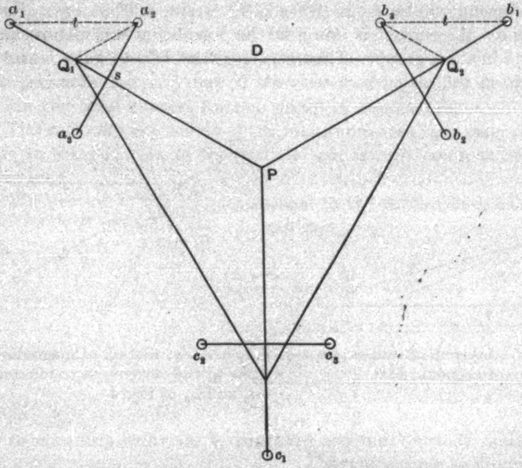

Fig. 4—Arrangement of three-part split conductors for three-phase line

from I to T. The factor 2 represents the effect of the fact that the wire is very long. The component of this magnetism perpendicular to the line $U\,S$ is

$$\frac{2\,I}{\sqrt{q^2+x^2}} \cdot \frac{x}{\sqrt{q^2+x^2}} = \frac{2\,I\,x}{q^2+x^2}.$$

The total flux of magnetism resolved perpendicular to $U\,S$ between points U and S will be

$$I\int\frac{2\,x}{q^2+x^2} = I\log\,(q^2+x^2)\,\Big|_{O\,S}^{O\,U} = 2\,I\log\frac{M}{N}.$$

From considerations of symmetry it is evident that at times when current in the *a* group is a maximum, at which times the current in the *b* and *c* groups are equal, the resultant magnetism at all points along the line a_1, P, Fig. 4, due to a_1, a_2, a_3 will be perpendicular to this line. It is further evident that the maximum magnetic field between the points *s* and the point *P* will be a maximum, when the current in the *a* group of conductors is a maximum. The value of I in the *a* group will then be $I \sin 90°$. At this time the current in the *b* group will be $I \sin (90° + 120°) = -\sin 30° = -\frac{1}{2}$ and the current in the *c* group will be $I \sin (90° + 240°) = \sin -30° = -\frac{1}{2}$. Furthermore the current is rising in the *b* group at this instant and falling in the *c* group. Thus the resultant effect of the *b* and *c* group on the magnetism between *S* and *P* is not changing at this time, showing that the resultant of the three groups is at a maximum as already stated.

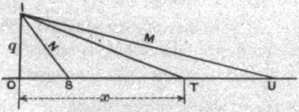

FIG. 5—Diagram of summation of magnetic flux

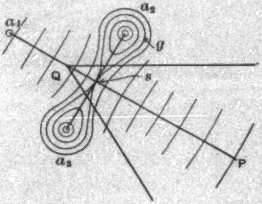

FIG. 6.—Distribution of magnetism due to the currents in conductors a_2 and a_3 of Fig. 4

Again since the currents in the *b* and *c* groups are negative when the current in the *a* group is a maximum, their effect on the magnetism cutting the line *S P* is added to that of the *a* group.

The form of the lines of force due to the currents in a_2 and a_3 only is shown in Fig. 6. The lines of force included between a_2 and *P* may be considered in two parts, that outside the line of force marked *g*, which can easily be measured along the line *s P*, and the part inside this line of force which can easily be measured along the line *s* a_2.

The total magnetism linked between conductor a_2 and *P* is the same as between either a_3 or a_1 and *P*. This is evident for a_3

from conditions of symmetry, but is strictly true of a_1 only when its ohmic resistance is 0. Any greater number of lines between a_1 and P than between a_2 and P will cause in the outer wire a greater counter electromotive force, which will reduce the current in a_1, since a_1 and a_2 are in parallel at both ends, and will increase the current in a_2 and a_3 until the resultant magnetism between a_1 and a_2 is O, the effects of current in all groups of conductors being considered. Any resistance in the conductors a_1, a_2, and a_3 will, however, tend to resist this division of current. The resistance effect will be small in large conductors such as would be considered in actual transmission problems. The conclusion is that the current in a_2 or a_3 is greater than one third of the total current. Let k be this corrective increment, that is, the current in $a_2 = I/3\ (1+k)$, I being the total current for one group of conductors.

The various components of the maximum resultant magnetism due to the currents in the various conductors can now be determined.

The portion of the magnetism due to the current in a_2 cutting the line $s\,P$ perpendicular thereto is

$$\frac{2\,I\,(1+k)}{3}\log\frac{M}{N},\text{ as above.}$$

$$=\frac{2\,I\,(1+k)}{3}\log\frac{\sqrt{\left(\frac{D}{\sqrt{3}}-\frac{t}{2\sqrt{3}}\right)^2+\left(\frac{t}{2}\right)^2}}{\frac{t}{2}}$$

$$=\frac{2\,I\,(1+k)}{3}\log\frac{\sqrt{\frac{D^2-Dt+t^2}{3}}}{\frac{t}{2}}=$$

$$=\frac{I\,(1+k)}{3}\log\left(\frac{4}{3}\cdot\frac{D^2-Dt}{t^2}\right)\text{ approx.}$$

But the current in a_3 causes this same amount of magnetism on the line $s\,P$, and that due to both a_2 and a_3 between s and P is

$$\frac{2\,I\,(1+k)}{3}\log\left(\frac{4}{3}\cdot\frac{D^2-Dt}{t^2}\right)\text{ approx.}$$

The magnetism inside of the line of force g due to the current in a_2 will cut the line $a_2\,s$ perpendicularly and equals

$$\frac{2\,I\,(1+k)}{3}\left(\log\frac{\frac{t}{2}}{r}+\frac{1}{4}\right)$$

where the term

$$\frac{2\,I\,(1+k)}{3}\quad\frac{1}{4}$$

is the inductance within the wire itself and where r = the radius of the conductor. Similarly the magnetism due to the current in a_3 between a_2 and s is

$$\frac{2\,I\,(1+k)}{3}\log\frac{t}{\frac{t}{2}}=\frac{2\,I\,(1+k)}{3}\log 2$$

Therefore the magnetism due to a_2 and a_3 between a_2 and s =

$$\frac{2\,I\,(1+k)}{3}\left(\log\frac{\frac{t}{2}}{r}-\log 2+\frac{1}{4}\right)=\frac{2\,I\,(1+k)}{3}\left(\log\frac{t}{4\,r}+\frac{1}{4}\right)$$

since the effect of a_3 along the line $a_2\,s$ is opposite to that of a_3.

The magnetism produced by the current in a_1 between a_2 and P will be

$$\frac{2\,I\,(1-2k)}{3}\log\frac{\frac{D}{\sqrt{3}}+\frac{t}{\sqrt{3}}}{t}=\frac{2\,I\,(1-2\,k)}{3}\log\frac{D+t}{\sqrt{3}\,t}$$

since the lines of force due to a_1 are circles about a_1.

The effect of the group b may be taken to be the same as though the three conductors were concentrated at the point Q_2. The magnetism between s and P due to the c group will be the same as the b group at this instant of time when the current in the a group is a maximum. The effect of the two groups between a_2 and P is

$$2\,I\log\frac{\sqrt{\left(\frac{D}{2}\right)^2+\left(\frac{\sqrt{3}\,D}{2}-\frac{t}{2\sqrt{3}}\right)^2}}{\frac{D}{\sqrt{3}}}\quad\text{approx.}$$

$$=I\log 3\ \text{approx.}$$

Summing all these components of the magnetism:

Total magnetism =

$$\frac{2\,I\,(1+k)}{3}\left[\log\left(\frac{4}{3}\cdot\frac{D^2-D\,t}{t^2}\right)+\log\frac{t}{4r}+\frac{1}{4}\right]$$

$$+\frac{2\,I\,(1-2\,k)}{3}\log\frac{D+t}{\sqrt{3}\,t}+I\log 3,\ \text{approx.}$$

$$=\frac{2\,I}{3}\left[(1+k)\left\{\log\frac{4}{3}\,\frac{D^2}{t^2}+\log\frac{t}{4\,r}\right\}\right.$$

$$\left.+(1-2\,k)\log\frac{D}{\sqrt{3}\,t}+3\log\sqrt{3}+\frac{1+k}{4}\right]\ \text{approx.}$$

$$=\frac{2\,I}{3}\left[(1+k)\log\frac{D^2}{r\,t}+(1-2\,k)\log\frac{D}{t}+\frac{1+k}{4}\right]\text{approx.}$$

$$=\frac{2\,I}{3}\left[(1+k)\left(\log\frac{D}{r}+\frac{1}{4}\right)+2\log\frac{D}{t}\right]\ \text{approx.}$$

Then the inductance = L

$$=\frac{2}{3}\left[(1+k)\left(\log\frac{D}{r}+\frac{1}{4}\right)+2\log\frac{D}{t}\right] \qquad (49)$$

These logarithms are natural logs to the base ε.

For a three-phase line without the split conductors, the inductance from one wire to the point P would be

$$2\log\frac{D}{r}+\frac{1}{2} \qquad (50)$$

So that the ratio of these two quantities (49) and (50) represents the change in the inductance due to the splitting of the conductors.

The capacity of the system with split conductors will be increased in substantially the same ratio that the inductance is decreased. The capacity can be determined by finding the work done against static charges on the several wires in moving a unit positive charge, from a_2 to P, for example:

As this work will integrate in exactly the same form as the inductance above (neglecting the inductance within the wire itself) the potential for a given charge between wires will be reduced by splitting the conductors in the same ratio that the inductance was reduced. But the capacity of the circuit is inversely proportional to the potential existing between wires for a given charge, so that the capacity is increased as the inductance is decreased.

There remains the determination of the quantity k. Referring to Fig. 4 the total flux between a_1 and a_2 or between a_1 and a_3 will be the same. This can be calculated by the methods already used.

The magnetism due to a_2 and a_3 between a_1 and s will be

$$\frac{4\,I\,(1+k)}{3}\log\frac{t}{\frac{t}{2}} = \frac{4\,I\,(1+k)}{3}\log 2$$

$$= \frac{2\,I\,(1+k)}{3}\log 2^2$$

The magnetism between s and a_2 due to a_2 and a_3 as before =

$$\frac{2\,I\,(1+k)}{3}\log\frac{t}{4\,r} + \frac{I\,(1+k)}{6}$$

Therefore the total magnetism between a_1 and a_2 due to a_2 and a_3 will be

$$\frac{2\,I\,(1+k)}{3}\log\frac{t}{r} + \frac{I\,(1+k)}{6}$$

The magnetism between a_1 and a_2 due to a_1 =

$$-\frac{2\,I\,(1-2\,k)}{3}\log\frac{t}{r} - \frac{I\,(1-2\,k)}{6}$$

The sum of these values

$$= 2\,I\,k\log\frac{t}{r} + \frac{k\,I}{2}$$

$$= 2\,I\,k\left(\log\frac{t}{r} + \frac{1}{4}\right)$$

The magnetism between a_1 and a_2 due to the b and c groups which this must balance will be

$$4\,I \log \frac{\sqrt{\left(\frac{D}{2}\right)^2+\left(\frac{\sqrt{3}\,D}{2}+\frac{t}{\sqrt{3}}\right)^2}}{\sqrt{\left(\frac{D}{2}\right)^2+\left(\frac{\sqrt{3}\,D}{2}-\frac{t}{2\sqrt{3}}\right)^2}}$$

$$= 2\,I \log \frac{D^2+Dt+\frac{t^2}{3}}{D^2-\frac{D\,t}{2}+\frac{t^2}{12}}$$

$$= 2\,I \log \left(1+\frac{3}{2}\;\frac{t}{D}\right) \quad \text{approx.}$$

That is

$$2\,I\,k\left(\log\frac{t}{r}+\frac{1}{4}\right)=2\,I\log\left(1+\frac{3}{2}\;\frac{t}{D}\right)$$

and

$$k=\frac{\log\left(1+\frac{3}{2}\,\frac{t}{D}\right)}{\log\frac{t}{r}+\frac{1}{4}} \quad \text{approx.} \qquad (51)$$

which completes the formula for the inductances of the split conductor, having three parts arranged as shown in Fig. 4.

In calculations of three-phase circuits with split conductors by the equivalent single-phase circuit, the ratio of inductances and capacities determined above should be used.

In case the conductor be split into two parts instead of three as above, the following formula can be deduced by the same methods.

Inductance between a_2 and $P = \log\frac{D}{\sqrt{3}\,t}\cdot\frac{D}{r}+\frac{1}{4}$, assuming that the two parts of the split conductor lie symmetrically on opposite sides of the line $s\,P$.

Other formulas can be easily derived for other arrangement of the wires of the two or three-part combinations or for single-phase circuits. The spiral arrangement of the split conductors will have little effect on the inductance as long as the distances between the centers of gravity of the groups are the same.

This completes the new formulas utilized in the companion paper. It is believed that these, especially the wave and split-capacity formulas will be found especially convenient and serviceable by transmission engineers.

DISCUSSION ON "OUTPUT AND REGULATION IN LONG-DISTANCE LINES," AND "CALCULATION OF THE HIGH-TENSION LINE." FRONTENAC, N. Y., JUNE 29, 1909

T. R. Rosebrugh (by letter): Mr. Thomas refers to the time required to work out formulas given by previous writers. The time occupied in making a calculation, however, consists of two parts: first, the verification of the formulas to be used, by a critical examination, for they may contain typographical errors, or be misunderstood; secondly, the actual computation. The longer and more unsymmetrical a formula is the more time one would in general take in checking it.

The following are simple, convenient, and flexible, yet give the general solution for the steady state:

$$E_1 = E_0 + z\,I_0 + \tfrac{1}{2}\,z\,y\,E_0 + \tfrac{1}{6}\,z^2\,y\,I_0 +$$

$$I_1 = I_0 + y\,E_0 + \tfrac{1}{2}\,y\,z\,I_0 + \tfrac{1}{6}\,y^2\,z\,E_0 +$$

two series converging in all practical cases quite rapidly, in which each symbol denotes a complex quantity according to Dr. Steinmetz' notation, E_0 and I_0 being for the receiving end E_1 and I_1 for the transmitting, and z and y are the quantities $r+x\,j$ and $g+b\,j$, respectively, for the whole line.

Whether it has occurred to anyone to publish this form of the solution I do not know, but it seems not to be so well known as it deserves.

In addition to these equations, those obtained by using a minus sign before each even numbered term may be employed in preference when the known end of the line (E_0, I_0) is transmitting power instead; this makes the power component of I_0 in both cases positive when E_0 is denoted by a positive real quantity.

Suppose in the first place that one condition only of the line is to be calculated, the least labor will then be expended by proceeding as follows:

Starting with I_0 (complex quantity) multiply it by z and this again by $y/2$. Similarly starting with E_0, multiply by y, and this product by $z/2$.

On looking at the two series it will be seen that following two zigzag lines the first three terms of voltage and current are now known, and simple addition will now usually determine both components of each with sufficient accuracy.

If the line be so long that the last term calculated above in either series is not small enough, proceed further along either or both zigzags until satisfied. It will be noticed that the successive factors for one zigzag are $\frac{z}{1}$, $\frac{y}{2}$, $\frac{z}{3}$, $\frac{y}{4}$, etc. and $\frac{y}{1}$, $\frac{z}{2}$, $\frac{y}{3}$, $\frac{z}{4}$ for the other.

Thus no labor is wasted, each multiplication giving one term, and the error is known to be much less than the last term calculated in the given series.

Secondly, if the calculation is to be made for several different conditions (which may be given for either end) it is easiest to find first the coefficients of E_0 and I_0 in the two series, and these are readily found numerically also, three multiplications only serving to determine what is required to the end of the fourth term in both series. In this simple manner A, B, C are found such that

$$E_1 = A\,E_0 + B\,I_0$$

$$I_1 = A\,I_0 + C\,E_0$$

hold for given conditions at receiving end and

$$E_1 = A\,E_0 - B\,I_0$$

$$I_1 = A\,I_0 - C\,E_0$$

for given power house conditions. These forms of the series are now conveniently ready to deal with any values of E_0 and I_0 which may be inserted.

To prove that the first series given are correct it is only necessary to remember that a Taylor's expansion requires merely the successive derivatives of the variable at one given point. Now since $\frac{dE}{ds} = z\,I$ and $\frac{dI}{ds} = y\,E$ everywhere on the line, (s being the distance from 0 in terms of the line as unit of length), these successive derivatives may be written down by inspection, and their values at the zero end are seen to be such that multiplication by $\frac{1}{2}$, $\frac{1}{6}$, $\frac{1}{24}$, etc. produce the terms of each series as stated, at the other end of the line where $s = 1$.

Intermediate conditions on the line may be found by retaining the proper powers of s. The two methods of calculation which take account of capacity, either all at the middle or divided equally between the ends, amount to taking three terms both of voltage and current, the former, however, includes also 3/2 of the fourth term of voltage, the latter also 3/2 of the fourth term of current.

Mr. Thomas' paper contains a recommendation to calculate three-phase transmissions by reference to a single-phase circuit in which all the quantities concerned are different from those of the actual three-phase circuit or its parts.

Would it not be better to calculate the actual circuit as a star arrangement; that is, each of the three wires with its own actual resistance, reactance, capacity to neutral, and leakage conductance as the line portion of a circuit carrying its share, namely one third of the power and at the star voltage?

It may perhaps be said that the recommendation is harmless, but the result of such propositions is apt to be, as has already occurred, that tables are prepared giving fictitious quantities for three-phase lines instead of the real ones. This leads to a state of affairs in which handbooks become unsafe to use, for such tables are apt to be given without adequate warning as to the special fiction they favor.

The paper deals with three distributed line constants but omits the fourth—leakage conductance. This may be taken into account and his formulas thus given greater generality as follows. Let r, x, g and b have their usual value as real numerics, and in this case z and y also the real values $\sqrt{r^2+x^2}$, $\sqrt{g^2+b^2}$ instead of complex quantities as above, and all six for the whole line.

For	Write
$\alpha x = \frac{R x}{2}\sqrt{\frac{2 p C}{p L+\sqrt{R^2+p^2 L^2}}}$	$\sqrt{\frac{z y+r g-b x}{2}}$
$\frac{p x}{v} = x\sqrt{\frac{p C\,(p L+\sqrt{R^2+p^2 L^2})}{2}}$	$\sqrt{\frac{z y-r g+b x}{2}}$
$\sqrt{\frac{\sqrt{R^2+p^2 L^2}}{p C}}$	$\sqrt{\frac{z}{y}}$
$\frac{p}{\alpha v} = \frac{p L+\sqrt{R^2+p^2 L^2}}{R}$	$\sqrt{\frac{z y+r g+b x}{z y-r g-b x}}$

One might gather from the reference to the perfectly uncharged line that the scope of the paper is sufficient to deal with transient states of the system; this, however, is elsewhere stated not to be the case.

The statement that the current produces a drop in the line proportional to the current and the square root of the impedance and inversely proportional to the square root of the capacity susceptance seems inadequate and misleading, for the factor omitted is also a function of the line constants for both terms involving the current.

In the investigation of the so-called split conductor the currents in the strands are taken to be different as indicated by the factor k, but there appears to be no reason given for neglecting the slight phase difference one would naturally expect between the currents a_2 and a_3, due to the revolving field in which they are situated.

However this may be, if the three strands are transposed so that each has an equal length in each position, then k becomes zero, and this phase difference vanishes also.

Checking by a different method the final result for L, and on the assumption that the strands are given a cyclical transposition, I obtain the same expression on the understanding that t is small in comparison with D.

It would then be a question whether for slight separation of the strands (if the construction should be adopted) the extra losses would be sufficient to justify the expense of the slight insulation necessary with transposition to avoid them.

V. Karapetoff: I think the first paper contains a good deal of what could be called prophetic vision. At the present stage of the development of exceedingly long transmission lines such prophetic pictures are as important to us as detailed investigations of the performance of such lines. It is necessary for us, and particularly for our leaders of industry, to have such clear mental pictures, before we can see these transmission lines realized in practice.

I would suggest that Professor McMahon's book of hyperbolic functions is a good book for engineers who wish to use hyperbolic functions in addition to plain trigonometry. It is a book which is easily readable, and what makes it particularly valuable to electrical engineers is the fact that the same problem on transmission line which is solved in Dr. Kennelly's article, in the 1895 TRANSACTIONS of the Institute, is worked out and considerably simplified in this book. In place of Dr. Kennelly's charts, Professor McMahon has calculated more accurate tables of hyperbolic functions of complex quantities, with double entry, so that the calculations are easily performed.

However, I think that all the possible mathematical methods should be open for the use of engineers. Some of us may prefer hyperbolic functions, others may prefer Dr. Steinmetz's method. Others again may prefer the treatment within the limits of plain trigonometry, as given in Mr. Thomas' paper. I do not think that we should limit ourselves to any specific method, because the temperaments and natural inclinations of engineers differ very materially. This may be likened to the case of two mechanics building similar devices. One would spend most of his time in making special tools with which to construct the device; the other would prefer not to make special tools, but to devote all the available time to building the device itself.

But even granting that Mr. Thomas's method of treatment is legitimate and useful, I do not believe that he did full justice to the method: the deductions can be considerably simplified. The paper will undoubtedly be referred to by many of us later on. Therefore, I would suggest that Mr. Thomas give the paper to some professional mathematician and ask him to go over it and simplify the equations.

John B. Taylor: In transmitting power with direct current, we are all familiar with the fact that the only limitation as to distance is the size and price of copper conductors. With alternating-current work we find other limitations. After obtaining the right of way and paying, say, a million dollars for this with steel towers, insulators, etc., we find that we can effectively put up only a certain size of copper wire. This is because the reactance of the circuit is reduced practically not at all as the wire is increased in size, and the reactance may be the limiting factor in the amount of power to be got over the line. Of course the reactance can be reduced to a certain extent, either by bringing the wires closer together, or by putting up a multiple circuit. The multiple circuit in its most efficient form means a distinct pole line, with perhaps another million dollars for duplicating right of way, steel towers, etc. Reduction of inductance by splitting the conductor, as suggested in the paper, may be effective; but this involves more dollars, and special construction of insulators and supports which have not been tried out.

The paper disappoints me from the fact that after reading it I find myself with no clearer physical conception of the interactions and reactions of distributed resistance, inductance, and capacity in the transmission line. This I think is due to the use of the term "energy" for something which is not energy, and the lack of any fixed direction of energy transfer as a reference, which allows Mr. Thomas to call the same current leading or lagging according to which way he looks at it. Receiving apparatus is also spoken of as *supplying* current and energy. This special use of terms and shifting point of view make it difficult to follow the exposition. I hoped that Mr. Thomas would give a clear mental picture of the changing values and phases of current and potential at numerous points of the long-distance, alternating-current line, which from one point of view is merely an indefinite number of condensers, reactances, and resistances connected together. If we can solve the more familiar case of reactive coil, tin-foil condenser, and resistance box on alternating current, by extension we should understand the long-distance transmission line. Determination of actual values may involve mathematics too difficult for many of us, but a rational understanding of what we are dealing with seems desirable before passing to the long equations.

Charles P. Steinmetz: I consider the extensive use of the terms leading and lagging power as one of the most valuable features in this important paper. For a number of years I have been trying to introduce these terms instead of the frequently employed terms "lagging current" and "leading current." Lagging power and leading power, or combined in one expression, *reactive power*, is a real, existing quantity, but not so reactive current, as lagging or leading current. There is no such thing as lagging current, absolutely; it is only relative. Referring to an induction motor under a given condition of operation, it may be said that the motor takes so many volt-amperes reactive power, but it cannot be said that it takes so many amperes reactive current for magnetization. Magnetizing current is wattless or reactive only with reference to the induced electromotove force, but it is very far from wattless with regard to the impressed electromotive force. Hence, applied to current and voltage, "reactive", "leading", and "lagging" are relative terms. This is particularly true in the case of a transmission line. For instance, in a 700-mile transmission line operating at 60-cycles, if the current and voltage are in phase at the generator, then at the receiving end the current will be approximately 90 degrees out of phase with the generator voltage; that is, the current from the line would be wattless in regard to the generator voltage. But it is not, obviously, wattless or reactive power; it is practically in phase with its own voltage at that place, the receiving end of the line; it merely means that the entire power has shifted 90 degrees, or, in other words, that the storage capacity of the line is sufficient to store the entire energy, and then send it out again at the receiving end, producing 90 degrees phase displacement. This feature makes the use of lagging current and leading current misleading and unsatisfactory in dealing with complex circuits.

Mr. Thomas' paper concludes that it is necessary, for economical transmission, to balance the leading and lagging energies of the line, and that balancing is done by adjusting the relations of voltage and current to the relations of inductance and capacity, so that the value of volts over amperes must be equal to the square root of inductance over capacity. This relation has a very simple physical meaning, which we must realize. It is the condition of free flow of electric power, the relation which exists for electric power in the transmission line as a circuit, which adjusts itself to change of conditions. For instance, if the electrostatic charge impressed upon the line by a lightning stroke readjusts itself by dissipation, or if the line discharges to ground, or an impulse or wave travels along the line, or if a sudden oscillation makes the line surge—in all these cases voltage and current are related as the square root of inductance and capacity. It will be seen, therefore, that the condition of maximum economy of power transmission is the relation of free flow of power.

It means, however, that for economic transmission, and more particularly for voltage regulation, we must have in these very long lines such methods of controlling the power-factor and the voltage at the receiving end that, at the economical load, the receiving circuit shall be non-inductive, and at light load the leading power of the line shall be supplied from the receiving circuit; that is, the receiving circuit feed leading current into the line, or, as it is usually expressed, the line sends lagging current into the receiving circuit. This necessitates a method of adjusting the power-factor by varying the phase relation of the load, so as to have the phase relation of the load change from lagging at light load, over non-inductive condition at the economical load, to leading at overload; in short, the well-known method of phase control is required to get maximum efficiency of transmission.

In long-distance transmission lines, as a general thing, this is not yet done to any extent, but it is common practice in those long-distance transmissions in which the receiving apparatus is specially suited for the automatic variation of phase relation; that is, in railway systems with converter sub-stations. There this method of phase control of the line is generally used as it gives the best regulation and best economy.

As a corollary, therefore, in conclusion 7, the non-synchronous machine, or, as commonly called, the induction generator, is referred to. This is a type of machine especially adapted to a load in which the synchronous apparatus controls the phase relation with the load. The induction generator naturally adapts itself to the synchronous phase controlling receiver.

As regards the computing formulas, there are a number of formulas that give fair approximations. One of the simplest is the following: first consider the entire line capacity as a condenser at the generator; this gives a simple, quick computation. Then consider the entire line capacity as a single condenser at the receiving end; this is also a simple and quick computation. By averaging these two approximations we come close to the actual condition. These combined computations are far simpler than a single computation with the condenser at the middle of the line; at the same time they give a closer approximation. To find out whether they are really close enough, the complete calculation should be made for a few points. However, these calculations may be checked by estimating the capacity (the charging current of the line) as a percentage of the full-load current. So long as the charging current is less than a certain percentage, perhaps 20 or 30 per cent of the full-load current of the line, these localized computations are fairly satisfactory. Beyond that the complete line equations must be used, as stated by Mr. Thomas.

These complete equations are not so formidable as they look at first sight, but can be modified to very simple expressions. The disadvantage of the general equations for computation is the existence of the exponential function, which must be evaluated. Some months ago Mr. E. J. Berg and I had occasion to look into the question of calculating long power transmission lines quickly, so as to get within a half-day complete curves for different loads and different power-factors of the load. We found that for practically any commercial line, up to 300 or 400 miles, or even more, almost a perfect approximation could be got by using the complete equation, but substituting for the exponential functions the first terms of their series, which eliminates the stumbling blocks of the computation. The simple equations resulting thereform will be found later in this discussion.

Paul M. Lincoln: The practical engineer approaches these two papers with an interrogation something like this—what is there in them that can be of assistance to the electrical engineer who is about to design a long-distance, power transmission line?

The answer to that question, as I see it, is that for present conditions, and for those which will arise in the immediate future, as far as we can foretell them, there is little or nothing contained therein that will be of assistance to him. But for conditions which are apt to arise in the distant future the discussion and the analysis made in papers may be of considerable value. Mr. Thomas has made a close and careful study of the conditions which will obtain when a transmission line contains a certain type of resonance. This resonance depends upon at least three conditions, all of which must be satisfied before resonance can obtain: first, there must be a given load transmitted over the line; secondly, that load must be at a given power-factor; thirdly, there must be a given voltage. These three conditions, at least, must be satisfied before the particular type of resonance which Mr. Thomas has discussed may obtain.

For conditions below full load there is not sufficient current to cause an excessive drop; for conditions above full load the drop will increase very rapidly as the load increases. This increase will be so rapid as to place a practical limit to the line capacity at its full load. Hence we will have a line whose most economical point is at load a; it cannot carry more than load a, for less of a load its regulation will not be so good as for load a. Such a condition must, to say the least, be inconvenient, and would probably result in such a handicap as to render useless the transmission line having such limitations.

Ralph D. Mershon: I have not had an opportunity to give this paper nearly the study I wanted to and that I intend to. There are one or two points in regard to it I would like to mention. If I remember rightly, Dr. Fleming made, at a much earlier date than any of those mentioned, a study of the effects of the distributed inductance and capacity of a transmission circuit.

Mr. Thomas makes mention of a paper by myself, and misinterprets it a little, I think. In that paper it was assumed that with unity power-factor at the middle of the line, or approximately at the middle of the line, the line loss would differ little from that for unity power-factor throughout the line and that such difference as did exist would be negligible in the problem I was considering. Such assumption greatly simplified the problem, and is permissible where large amounts of power are transmitted. It was also assumed that the synchronous motors would be designed to give the requisite voltage regulation.

This brings up a point which, so far as I have been able to study his paper, Mr. Thomas seems to have neglected. A synchronous motor used at the end of a line to regulate the power-factor of the line is not equivalent to a condenser; it behaves quite differently. When the voltage increases on a condenser the current to the condenser increases. When the voltage impressed upon an over-excited synchronous motor increases, the leading current to the motor *decreases*, and with further increase of impressed voltage the current passes through zero and then becomes a lagging current which *increases* with the impressed voltage. As a result, such a motor may improve or may impair the regulation; meaning by *regulation* the inherent regulation—the maximum change in voltage if full load, say, be thrown off suddenly and no adjustment made in the system. If the inherent regulation of the line, and the synchronous motor at the end of it, happen to be the same, then the regulation of the combination of line and motor will be that of either. If the inherent regulation of the line be worse than that of the synchronous apparatus, then the resultant regulation will be better than that of the inherent regulation of the line, and not so good as that of the synchronous apparatus, and conversely. Synchronous apparatus tends to make the regulation of the system the same as that of itself; better or worse as the case may be.

There would be great mechanical objection to the split conductor Mr. Thomas proposes. There may be another objection in the limitation its use may put upon the permissible line voltage, as governed by the critical point or point at which the air begins to break down, as against the voltage which could be used if a single conductor of larger diameter were employed. The mechanical objections Mr. Thomas has already mentioned, but I think that when it comes to making figures as to the increased cost involved in the line structures and construction generally by the use of three cables, it will be found that, because of the greater wind forces resulting, especially if the cables gather sleet, the increased cost will make the use of the split conductor extremely objectionable, if not absolutely prohibitive.

Henry W. Fisher: About a year ago we had occasion to make some calculations on a proposed 60-mile cable transmission line to operate at 60,000 volts. The power to be delivered was 42,000 kw. at 80 per cent power-factor. On account of the high capacity and low self-induction of the line the calculated power-factor at the generator was practically 100 per cent. In some calculations the load was leading, in others lagging.

Calculations were made with half the capacity concentrated at each end and also, according to Dr. Steinmetz' recommendation, with one sixth of the capacity at each end and two thirds in the middle.

The calculated results based on both of these assumptions were not materially different.

J. B. Whitehead (by letter): The use of approximate formulas should invariably be safeguarded by consideration: first, of the range of values within which the approximation holds true, and the magnitude of variation due to the correcting factors without this range; and, secondly, the degree to which experiment and experience have shown the approximate formulas to be sufficiently correct.

The author of these papers has performed a valuable service in presenting his wave formulas as checks upon the use of the split-capacity formula. Considering his comparison of the two types of formula as given in Table I, one is surprised and rather relieved to find the small differences that are involved. It should be pointed out, however, that the author has considered ohmic resistance, inductance, and capacity only. The losses between lines, over insulators, and in other kindred phenomena have been neglected. These losses would appear as a conductance or parallel connected resistances in the development of a formula taking them into account. The suggestion of the author to subdivide the individual wires of the line into several others would naturally lead to an increase in the insulator loss, and without further modification would also lead to circulating or secondary currents in the several branches of one line, due to inductive action of the others. My feeling after reading these two papers is that a series of accurate measurements on existing lines would be of first importance for answering the questions which are raised.

I find the author's standpoint in the description and explanation of the phenomena as given in the first paper rather confusing, by reason of the apparent separation of the energy into three components. I venture to call attention to several apparent inconsistences which result. Energy and voltage drop or rise appear to have the same physical dimensions. It may also be asked from what quantity involved are the phases of various currents, electromotive forces, and energies to be reckoned; that is, with reference to what quantity are the "leading and lagging" energies leading and lagging? We are asked on one page to note that the leading and lagging energies are equal and opposite when the load power-factor is equal to one, and then on the next page we are cautioned to remember that the leading and lagging energies have no necessary relation to the leading or lagging current in the load. We are also asked to imagine that the energy for charging the line flows against the energy which represents the power transmitted. Is it not the case that in the transmission of power the resultant flow of energy is in one direction? The distinction is also drawn between true power and leading and lagging energies, the inference being that these latter are wattless. My question then is, why call them energies? We are also told that in one instance the synchronous machines at the receiving end supply all of the load lagging current except enough to charge 300 miles of the line.

In calling attention to these few difficulties of my own, I have no wish to depreciate the author's valuable contribution to our knowledge of long-distance transmission problems. I wish only to make a plea for the retention of current and electromotive force as standards of reference where variation with time is involved, and the direction of the resultant flow of energy where variations in space are involved. If the instantaneous energy is of interest, Poynting's theorem based on Maxwell's equations that the flow of energy is in the medium and perpendicular at all points to the electric and magnetic vectors makes it possible to picture the flow of energy at any point in a line in terms of the instantaneous values of current and electromotive force.

C. F. Scott: I think Mr. Thomas deserves special credit for taking what is apparently a simple problem, which most of us have probably regarded as having been satisfactorily solved, and going into it deeply and working it out more fully, to determine what results may be encountered when new conditions may be reached in the future. It is the experience in all power transmission work, that when we go up to a higher voltage, new points, which have sometimes had an unimportant bearing, or which apparently have not been thought of before, force themselves into great prominence; and it is well to go over these problems very carefully, as is done here, so as to determine actually what these conditions are.

A few points have been raised in the discussion which it seems to me are taken care of. Mr. Lincoln, for example, suggested that the nature of the load was such that it was hard to get stable and definite conditions, and that if the conditions were properly established for one load, they would not be right for other loads. The important condition is full load, so that the line will transmit the full-load energy with a high efficiency; it is often of minor consequence what the efficiency is at lesser loads.

Mr. Mershon raised the point that synchronous machines are different from condensers, because when delivering different amounts of current, they were liable to give different voltages. But as Mr. Thomas will use the synchronous machine at the receiving end of the line, it is to be loaded at practically constant potential, and therefore it seems to me that these variables will probably not appear. The synchronous machine at the end of the line is not dependent upon the various voltages and currents coming in over the line, but it of itself is to be made the important voltage regulating element in the system. We may consider, I think, that we have two kinds of current in the system, one, the power current, comes from the generating station, and the other current that has been called by various names this morning. I will, however, use the familiar term wattless current. That has to be supplied from somewhere also, and Mr. Thomas supplies it at the receiving end. Consequently, the power current will be generated at one end of the line, and the wattless current at the other end of the line by synchronous motors, and the latter may control the voltage at the receiving end, which appears an ideal relation.

It occurs to me that possibly two wires as a single conductor would accomplish the same effect as the three proposed by Mr. Thomas.

I have been impressed with the mathematical part of this paper. I think Mr. Thomas is to be congratulated in not mixing the two things together—the engineering conclusions and the mathematical methods. I was in New York a few days ago, and I met a consulting engineer who said he had been going over these papers and found they could be very much simplified. The first gentleman who opened the discussion this morning said that the matter given in the papers could be presented in a much simpler way. He went to the blackboard to prove it. The next speaker said the matter could be presented in a much simpler way, and he covered the blackboard twice. Another professor said it was a simple thing to buy a book and read all about it, and Dr. Steinmetz then said the purpose of all this mathematical demonstration is to show that it is really not needed at all.

W. A. Del Mar: I wish to call attention to the fact that in neglecting leakage Mr. Thomas has missed an opportunity to make his equations homogeneous and has complicated rather than simplified them by this omission. A set of equations due to Dr. H. Pender* takes leakage into account with the result that the final equations are more simple than those given in the paper under consideration.

Furthermore, Dr. Pender's solution is considerably simplified by the introduction of the power-factor angles of the line impedance and leakage admittance. The equations are put in such form as to give a clear physical conception of the processes, a quality lost by Mr. Thomas' rather lengthy expressions. It is unfortunate that Dr. Pender's article did not appear in the Proceedings where it could be discussed and freely compared with Mr. Thomas' paper and I hope that this brief contribution will serve to attract the attention of the Institute members who may have read the latter and not the former.

A. E. Kennelly: These papers are of great importance, if only because they show how much labor is involved in the computation of the voltage and current distribution over a long line having distributed resistance, inductance, leakance and capacity, when hyperbolic functions are avoided. In the opening paragraphs of the first paper, the author intimates that the methods which have been suggested hitherto for making such computations are long and unpractical. He proceeds to offer what he considers to be practical working formulas for working out such problems. These practical formulas recommended to us as superior to all preceding formulas are collected in one place.

There can be no doubt that the voltage and current distribution over long lines worked at a single alternating-current frequency in the steady state can be computed by these formulas, and the paper will be useful to engineers if only in the collection of these formulas. It is, however, open to discussion whether these formulas are the best for engineers. These working

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**Electrical World*, July 8, 1909.

formulas are so long that the voltage and current equations have first to be split into two parts (V_0 and $V_{\frac{\pi}{2}}$), or (I_0 and $I_{\frac{\pi}{2}}$), the square root of the sum of whose squares is the final voltage or current; while the formula for each component is then so long that it has to be printed lengthwise to the page. It is here contended by the speaker that such methods of computation are deterring and forbidding. They are fearful even to look upon, and the chances of making numerical mistakes in such long unwieldy equations are comparatively great. Fortunately, there are much simpler formulas for reaching the same results.

If the voltage to be supplied at the distant end of a line is e volts and the current to be supplied there is i amperes, at a given power-factor and phase-angle with respect to e; then it has been shown by the speaker* that the voltage E and current I at the sending end of the line are respectively:

$$E = e \cosh \theta + i\, z_0 \sinh \theta \qquad \text{volts} \angle \quad (1)$$

$$I = i \cosh \theta + (e/z_0) \sinh \theta \qquad \text{amperes} \angle \quad (2)$$

where z_0 is the surge impedance of the line:

$$z_0 = \sqrt{\frac{r + j\, l\, \omega}{g + j\, c\, \omega}} \qquad \text{ohms} \angle$$

or as a first approximation

$$z_0 = \sqrt{\frac{l}{c}} \qquad \text{ohms}$$

and $\theta = L\, \alpha$ is the " hyperbolic angle " subtended by the line where L is the length of the line in miles or km. and α is the attenuation constant:

$\alpha = \sqrt{(r + j\, l\, \omega)\ (g + j\, c\, \omega)}$ " hyperbolic radians " per mile or km.

also r = the linear resistance of the line (ohms per mile or km.)
l = the linear inductance of the line (henrys per mile or km.)
g = the linear leakance of the line (mhos per mile or km.)
c = the linear capacity of the line (farads per mile or km.)
$\omega = 2\, \pi\, n$ = the angular velocity (radians per sec.)
n = frequency impressed on line (cycles per second).
$j = \sqrt{-1}$

Equations (1) and (2) are the equivalent of Mr. Thomas' formulas (40), (41), (42), (43).

If we should attempt to solve plane triangles, in the regular work of surveying, without the use of circular functions, (circular sines, cosines, tangents, etc.,) that is, without the use of trigometrical tables, we could do it by roundabout, long and tedious methods, but the contrast between such methods and those we actually use would be marked. Similarly, hyperbolic trigonometry is as natural and as essential to alternating-current line computations as is ordinary circular trigonometry to the surveyor's work. Hyperbolic trigonometry is just as easy as circular trigonometry, and can be grasped and handled practically with very little extra effort by the engineer who already grasps and handles circular trigonometry. It is true that our tables of hyperbolic sines cosines, tangents, etc. of vector or complex arguments are still very deficient; but even when we have to work out the hyperbolic sines and cosines of formulas (1) and (2) for ourselves, without aid from tables, I contend that these formulas are much more practical, direct, and easy to handle without mistakes, than the long formulas of the paper just read.

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* " On the Fall of Pressure in Long-Distance Conductors," by A. E. Kennelly. *Electrical World*, Vol. XXIII, No. 1, p. 17, Jan. 6, 1894. also *The Electrician*, London, Vol. 32, Jan. 5, 1894, pp. 239–240. " Resonance in Alternating-Current Lines," by E. J. Houston and A. E. Kennelly. TRANSACTIONS American Institute Electrical Engineers, Vol. XII, pp. 133—159, April 17, 1895.

Hyperbolic tables are available already, however, in the following cases:

(1) where $\omega = 0$, or direct currents are used.

(2) where $l = 0$ and $g = 0$*; or in well insulated cables of negligible inductance.

(3) where $r = 0$ and $g = 0$; or where the line has negligible conductor and dielectric losses.

It is to be hoped that, before long, suitable tables of hyperbolic complex quantities may be available for engineers. Meanwhile, however, a hyperbolic sine or cosine of the complex angle $\boldsymbol{\theta}$, subtended by a line, can be computed by regular rules in a few minutes.

As pointed out in the papers before us, it is unnecessary in the great majority of cases to compute alternating-current line voltages and currents by the accurate formulas; whether those formulas be as given in (40), (41), (42), and (43) or those just given at (1) and (2) above. Lines are not long enough and fundamental frequencies are not high enough in power transmission work to make this refinement necessary. It is quite sufficient either to lump all the leakance and capacity in one condenser at the electrical middle point of the line; or, as in the paper, to split it into two equal condensers, one at each end of the line, and then to treat the line as a choking coil with condenser leak or leaks. If, however, higher harmonic frequencies have to be considered in long power-transmission line, it may be necessary to use the correct formulas of distributed capacity. Moreover the correct formulas are nearly always necessary in telephony, even on fairly short lines, owing to the high frequencies there employed.

The speaker has shown that the Π — conductor, or split-condenser representation of a line, may be readily corrected for the lumpiness-error; so as to give correct results, just as though the fuldistribution formulas had been used.* The correct values of the equivalent T and equivalent Π are given below:

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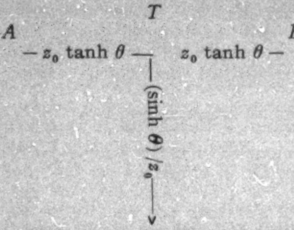
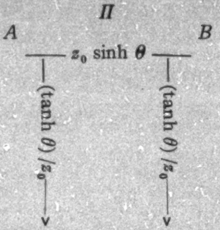
* The Alternating-Current Theory of Transmission Speed; and Table appended thereto. International Electrical Congress of St. Louis, 1904, Vol. I, pp. 68—105.





Here A and B are the terminals of the equivalent line, and $\theta = \boldsymbol{\theta}/2$, or is the hyperbolic-angle subtended by half the line. The total line impedance of the T is $2\, z_0 \tanh \theta$ and of the Π is $z_0 \sinh \boldsymbol{\theta}$ ohms. The total admittance of the capacity and leakage in the T is $\frac{\sinh \boldsymbol{\theta}}{z_0}$ mhos and of the Π, $\frac{2 \tanh \theta}{z_0}$ mhos. Since the corresponding impedances and admittances in the uncorrected or nominal T are $2\, z\, \theta$ and $\boldsymbol{\theta}/z_0$; while for the nominal Π they are respectively the same; viz., $z_0\, \boldsymbol{\theta}$ and $2\, \theta/z_0$; it follows that the lumpiness-correcting operators are the vector ratios $\frac{\tanh \theta}{\theta}$ and $\frac{\sinh \boldsymbol{\theta}}{\boldsymbol{\theta}}$, which are 1 for indefinitely short lines; but which may reach either large or small positive or negative values when θ and $\boldsymbol{\theta}$ are large.

These formulas, for the correct or equivalent-Π, form a fitting addition to the formulas in the paper on the split condenser method, or nominal-Π, method.

It is pointed out in the paper that the linear capacity of a split-conductor circuit is increased as its linear inductance is diminished. It is not generally known, and perhaps may not have been noticed by electrical engineers, that there is a very simple proposition connecting the linear inductance and capacity of any uniform conducting aerial circuit; namely, that the linear capacity in C. G. S. electrostatic units is the reciprocal of the external linear inductance in C. G. S. magnetic units. If l be the linear inductance of a uniform line in abhenrys per cm., counting only the effect of flux external to the conductor, and ignoring whatever additional inductance may be due to flux inside the wire; then if c be the linear capacity of the line in statfarads per cm., ignoring the capacity of the insulators, or other accidental condenser loads; then $l = 1/c$ or $c = 1/l$. This proposition depends on the fact that the velocity of electromagnetic wave propagation over any such aerial line is theoretically, $v = 3 \times 10^{10}$ cm./sec. very nearly and that, thus far, experimental observations have confirmed the theory. Moreover, it is known that this velocity of transmission $v = \frac{1}{\sqrt{l\,c}}$ cm/sec. where l and c are the linear inductance and capacity of the line both in magnetic units; *i.e.* in abhenrys per cm. and abfarads per cm. Consequently $c = 1/l\,v^2$ abfarads per cm.; but if we multiply the number of abfarads per cm. by v^2, we obtain, by definition, the same linear capacity expressed in statfarads per cm.; so that $c = 1/l$ statfarads per cm.

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* Artificial Lines for Continuous Currents in the Steady State by A. E. Kennelly. *Proceedings of the American Academy of Arts and Sciences.* Vol. 44, No. 4. Nov. 1908, pp. 97—130.

The Influence of Frequency on the Equivalent Circuits of Alternating Current Transmission-Lines, by A. E. Kennelly. *Electrical World.* Jan. 21, 1909. Vol. 53, No. 3.

This proposition enables us, in any uniform distribution of overhead line conductors; unsplit or split, to choose whether we shall compute the external linear inductance of the system, or the linear capacity, and then the other quantity follows as a simple reciprocal. Correction must subsequently be made for the internal inductance of the conductors, and for any load condensers, or insulator capacities, in the system. In the case of the paper before us, it is the inductance of the new conductor arrangement which has been worked out; so that the capacity follows at once, and clearly increases as the inductance of the line has been diminished by the wire-splitting.

P. H. Thomas: Mr. H. G. Stott has made a valuable suggestion in connection with the starting of non-synchronous generators; namely, that the machines can be built for both synchronous and non-synchronous operation, the revolving field being provided with the ordinary direct-current magnetization, and with the short-circuit squirrel-cage winding in addition. The line could then be started up from the direct-current, independent-field excitation, and when the synchronous machines were started the field circuit could be opened and the short-circuit winding would make the machine operate as a non-synchronous generator.

In the discussion a good deal of time is spent on the terms "leading energy" and "lagging energy." Under the circumstances I do not think it worth while to spend much time in further discussing those points. Briefly, the reason I use the terms is this: the effect of the capacity is a leading current in regard to the generator; the effect of the inductance is a reactance voltage. They cannot be spoken of both as leading or lagging current, leading or lagging voltage; they are different in character but both represent energy, and they balance as energy. A volt cannot be balanced against an ampere, but the energy of one phase can be balanced against the energy of another phase. Both represent real energy, but not of course energy usable in the load circuits.

I wish to call attention to one very excellent equation or formula for the calculation of the line not referred to in the paper, and which takes account of distributed inductance and capacity. This is given by Dr. Kennelly in the *Electrical World* in 1895. This formula makes use of vectorial quantities and involves hyperbolic functions. While extremely simple in form and very advantageous in theoretical analysis, its use requires a knowledge of vectorial algebra and hyperbolic functions and is not nearly so simple for numerical calculations as would seem from its form.

I wish to say again, as stated in the paper, that the derivation here given is not intended as a novel mathematical procedure, but merely as a straightforward derivation by the ordinary mathematical processes in common use among the majority of engineers, of a practical formula easily understood and conveniently used in engineering calculations.

Mr. Mershon has raised the question whether the relatively small sized individual wires of the divided conductor method described in the first paper would mean serious loss directly into the atmosphere. While I have no actual data on which to base an opinion, I should expect a gain rather than a loss in this feature since the divided conductor acts, in other relations, in effect like a larger conductor.

T. Dalemont (by letter): The method set forth by Mr. P. H. Thomas for the calculation of high-tension lines with capacity presents the advantage of doing away with vector diagrams into which errors so easily creep. But in this calculation the exponential and hyperbolic functions are not eliminated. It occurs to me that it might be of interest to call attention to a very simple method for calculating lines where the capacity effects are not negligible, and where they are to be considered as evenly distributed along the line. This method was suggested by Mr. André Blondel,* as far back as 1906. He based it on the fact that at every point of a line fed at the extremities by a sine electromotive force, the oscillations of the electromotive force and the current are both sine, and that each of them is the result of two waves flowing in opposite directions. One of these two waves is produced at the generating point, while the other is a reflex of the first, after this latter has reached the extremity of the line. Passing along the line, they both undergo simultaneously a damping and a phase rotation resulting from the combined effect of the self-induction and the capacity.

The equations of the second degree, differential equations of the tension, and of the current at point x from the end of the line are well known, and their solutions are expressed as follows:

$$V = A_1\, e^{a x} \sin\,(p\,t + b\,x - \alpha) + B_1\, e^{-a x} \sin\,(p\,t - b\,x - \beta) \qquad (1)$$

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* C. F. A. Blondel, Calcul designes avec self-induction et capacité. *Eclairage Electrique*, 1906, XLIX, p. 121. *Lumiere Electrique* T. I. (2d serie) p. 395.

In this, A and B are constant values and α, β are constant phase angles determined by the conditions at the extremities: On the other hand we have:

$$a = \frac{1}{\sqrt{2}} \sqrt{-p^2\,c\,l + r\,g + \sqrt{(p^2\,l\,c - g\,r)^2 + (p\,c\,r + p\,l\,g)^2}}$$

$$b = \frac{1}{\sqrt{2}} \sqrt{p^2\,c\,l - r\,g + \sqrt{(p^2\,l\,c - g\,r)^2 + (p\,c\,r + p\,l\,g)^2}}$$

In this r is the resistance per unit of length,
L the inductance, " "
c the capacity " "
g the conductance (corresponding for instance to the losses by ionization)
p the pulsation of the current.

The foregoing may be easily verified by differentiating the equation of V relatively to x and t and introducing the values obtained into the differential equation (1) given by Mr. Thomas, (equation (1)). Another term "$r\,g\,v$" must however be added to the second member if the conductance is negligible.

The developments of the transformation are the same as those which Mr. Thomas mentions, and the equations are not altogether different from his. We see for instance that $b = \frac{p}{v'}$ where v' is one of the values of v deduced from equation 10.

In the same way, we find for the current

$$i = \frac{A_1}{m}\, e^{ax} \sin\,(p\,t + b\,x - \underset{+\gamma}{\alpha +})\ \frac{B_1\, e^{-ax}}{m} \sin\,(p\,t - b\,x - \underset{+\gamma}{\beta +}) \quad (2)$$

where

$$m = \sqrt{\frac{a^2 + b^2}{g^2 + p^2\,c^2}}$$

$$\gamma = \text{arc}\,t\,g\,\frac{p\,c}{g} - \text{arc}\,t\,g\,\frac{b}{a}$$

m is therefore a factor of impedance. We may thus express the tension at any point at a distance x from the receiving end (and not from the generator end) by the sum of two vectors:

$$U_x = (A_1\, e^{ax})_{(+bx)} + (B_1\, e^{-ax})_{(-bx)}$$

The vectors $A_1\,e^{ax}$ and $B_1\,e^{-ax}$ having turned respectively through an angle of $(+b\,x)$ and $(-b\,x)$ from the position which each occupied for $x = 0$.

In the same way, the current at point x will give:

$$I_x = \frac{1}{m}\,[(A_1\, e^{ax})_{(bx+\gamma)} - (B_1\, e^{-ax})_{(-bx+\gamma)}$$

To find the values of A_1 and B_1 we must make $x = 0$, giving $U_x = U_1$ and $I_x = I_1$ (1); U_1 is the star tension and I_1 the current in each wire at the receiving end.

We thus find:

$$[A_1] = \left[\frac{U_1}{2}\right] + \left[\frac{m\,I_1}{2}\right] \quad (\text{turned} - \gamma)$$

$$[B_1] = \left[\frac{U_1}{2}\right] - \left[\frac{m\,I_1}{2}\right] \quad (\text{turned} - \gamma)$$

These two expressions enable us to determine A_1 and B_1 by a simple diagram.

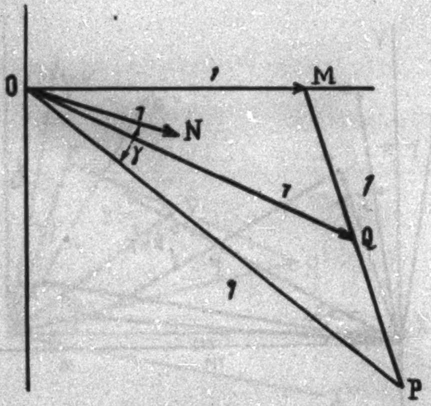

FIG. 1

In Fig. 1 $OM = U_1$; $ON = I_1$; $OP = m\,I_1$ turned through the angle $-\gamma$ and we obtain A_1 and B_1 in the lines OQ and MQ, which are half the sum and half the difference of the vectors U_1 and $m\,I_1$.

First case. Line at no load. $I_1 = 0$ (Fig. 2). The sum of A_1 and B_1 is U_1, and the difference, 0. Then $A_1 = B_1 = \frac{U_1}{2}$. Let $OM = A_1$, $MO = NM = B_1$ and $ON = U_1$. To find the values of the tension and the current at point x, we need only recall what has been said above.

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* I would here call attention to the fact that the equations are established on the supposition of a common return conductor of nil impedance, and that consequently U_1 is not the tension between the lines, but the tension between each wire and the centre of the assumed return.

In Fig. 2 $O p = \frac{U_1}{2} e^{ax}$, vector turned through the angle $(+b x)$ from 0, is drawn, and in the same way $P q = \frac{U_1}{2} e^{-ax}$. In carrying $p r = p q$, we obtain $o r = m I_x$, and finally $o s' = \frac{o r}{m}$ turned through an angle of γ, gives the value of I_x.

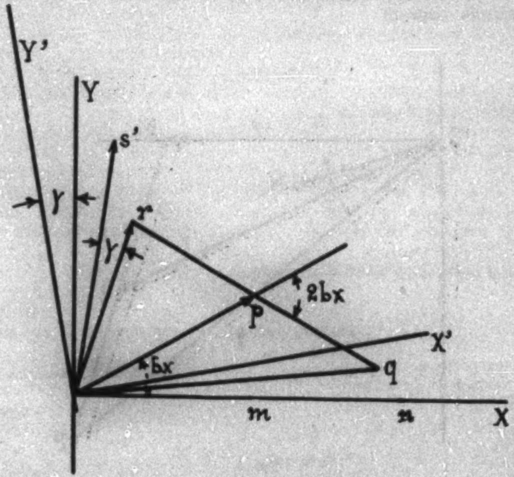

FIG. 2

Second case. Line at short-circuit. $U_1 = 0$ (Fig. 3). Let $O N = I_1$ the short-circuit current, and $A_1 = B_1 = O M = \frac{I_1}{2}$.

We obtain as above, at distance x from the receiving end,

$$O p = \frac{I_1}{2} e^{ax} \qquad P r = \frac{I_1}{2} e^{-ax}$$

The vector $O q' = J_x$ gives the short-circuit current in size and phase at point x.

$O r = \frac{1}{m} V_x$. V_x is the short-circuit tension at point x, but this vector must be multiplied by m and turned through the angle $-\gamma$ to obtain V_x in size and phase.

It will be noticed that the vector A_1 may be considered as the resultant of the two components $\frac{U_1}{2}$ and $\frac{m\,I_1}{2}$, the latter turned through an angle of $-\gamma$.

The same applies to B_1.

Finally U_x may be considered as the resultant of 4 vectors:

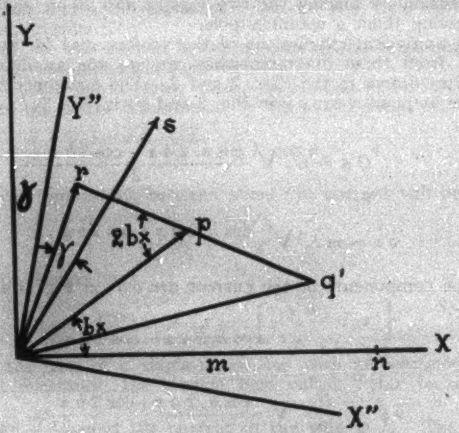

FIG. 3

$\frac{U_1}{2} e^{ax}$ turned through the angle $+b\,x$

$\frac{U_1}{2} e^{-ax}$ " " " " $-b\,x$

$\frac{m\,I_1}{2} e^{ax}$ " " " " $+b\,x$

$\frac{m\,I_1}{2} e^{-ax}$ " " " " $-b\,x$

It will be seen in any case, that if we make $A_1 = B_1 = \frac{U_1}{2}$

the two first terms would have for resultant, the tension obtained at the distance x when $I_1 = 0$ (at no load), which would be.

$$(U_x') = (A_1\, e^{ax})\ (b\, x) - (B_1\, e^{-ax})\ (-b\, x).$$

In the same way, if we make $A_1 = B_1 = \frac{I_1}{2}$ that is $U_1 = 0$, (short-circuit), the resultant of the two last terms will be:

$$(U''_x) = (A_1\, e^{ax})_{(bx)} - (B_1\, e^{-ax})_{(-bx)}$$

By a similar method, the current is brought back to its two components at no load and at short-circuit.

We may finally determine the resultant vectors of the current and tension by placing the two Figs. 2 and 3 on each other and giving them a common pole.

The analytical expressions of the vectors may be easily deduced from these diagrams when we use the auxiliary axis, which are drawn in the Figs. 2 and 3. The components of the tension at point x are $o\, q$ in Fig. 2 and $o\, s$ in Fig. 3. where,

$$O\, q = U_1 \sqrt{\frac{\cos h.\, 2\, a\, x - \cos 2\, b\, x}{2}}$$

and

$$o\, s = m\, I_1 \sqrt{\frac{\cos h.\, 2\, a\, x + \cos 2\, b\, x}{2}}$$

and the components of the current are $o\, q'$ in Fig. 3 and $o\, s'$ in Fig. 2.

$$o\, q' = I_1 \sqrt{\frac{\cos h.\, 2\, a\, x - \cos 2\, b\, x}{2}}$$

$$o\, s' = \frac{U_1}{m} \sqrt{\frac{\cos h.\, 2\, a\, x + \cos 2\, b\, x}{2}}$$

The vector angles may also be determined:

(angle between $o\, q$ and $o\, s$) $\phi = \text{arc}\, t\, g \left(\frac{\sin 2\, b\, x}{\sin h\, 2\, a\, x}\right) - (\gamma + \phi_1)$

(angle between $o\, q'$ and $o\, s$) $\Sigma = \text{arc}\, t\, g \left(\frac{\sin 2\, b\, x}{\sin h\, 2\, a\, x}\right) + \gamma + \phi_1$

In these expressions ϕ_1 is the phase angle at the receiving end, or in other words $\cos \phi_1$ is the power-factor of the receiving circuit. All these expressions will be met with in calculating the following line.

⁂

Let us take the line which Mr. Thomas gives as an example:

Transmitted power	40,000 kw.
Length of transmission	700 miles
Frequency	25 cycles
Tension between two wires at receiving end	150,000 volts
Power-factor	.918
Distance of wires	12 ft.

In his calculation, Mr. Thomas replaced the three-phase line by a single-phase line which transmitted half the power with the same tension, as that existing between wires. In the present calculation, the three-phase line was replaced as already mentioned, by a single-phase line, one conductor of which was similar to each of the conductors in the three-phase line, while the other had a nil resistance. We see that this should give the same results.

Let V_1 be the tension between wires of the three-phase line,
I_1 the current in each wire
$\cos \phi_1$ the power-factor of the distributed power.

Half of the power transmitted by the single-phase will be:

$$\frac{\sqrt{3}}{2} V_1 I_1 \cos \phi_1$$

With the tension V_1 between wires, the current will be:

$$I_1' = \frac{\sqrt{3}}{2} I_1$$

and the tension drop:

$$[V'] = [I_1' z'] = \left[\frac{\sqrt{3}}{2} I_1 z'\right]$$

In the case of a single-phase line with an assumed return of nil resistance, the tension here called "star tension" is:

$V_1'' = \dfrac{V_1}{\sqrt{3}}$ and the current in the wire is I_1. The tension drop is $[V''] = I_1 z'' = \frac{1}{2} I_1 z'$, the same therefore as in the preceding case.

We first calculated the current in each wire

$$I_1 = 167.5 \text{ amperes,}$$

and the star tension at the receiving end, $U_1 = 86.700$ volts. We will adopt the same conductor as that employed by Mr. Thomas.

The resistance r per mile of line is 0.085 ohm.
" reactance " " " " 0.309 "
" impedance " " " " 0.321 "

Admittance per mile, $w = \sqrt{g^2 + p^2 c^2}$

If g is neglected, we have: $w = p c = 2.386 \quad 10^{-6}$

We next calculated the auxiliary constant:

$$q = p^2 l c - g r \quad \text{or } p^2 l c \quad \text{if } g = 0$$

In the present case, we have $q = 0.737 \quad 10^{-6}$
The damping coefficient:

$$a = \sqrt{\frac{w z - q}{2}} = \sqrt{\frac{2.386\ 10^{-6} \times 0.321 - 0.737\ 10^{-6}}{2}}$$

$$= 0.12\ 10^{-3}$$

$$b = \sqrt{\frac{w z + q}{2}} \quad = 0.865\ 10^{-3}$$

Coefficient of influence of the current on the electromotive force: $m = \sqrt{\frac{z}{w}} = 366.$

Auxiliary factors: (x being here the net length of the transmission, 700 miles).

$$\alpha = \sqrt{\frac{\cos h\, 2\, a\, x + \cos 2\, b\, x}{2}} = 0.825$$

$$\beta = \sqrt{\frac{\cos h\, 2\, a\, x - \cos 2\, b\, x}{2}} = 0.572$$

Auxiliary angles:

$$\gamma = \operatorname{arc} t g \frac{p c}{g} - \operatorname{arc} t g \frac{b}{a} = \frac{\pi}{2} - \operatorname{arc} t g \left(\frac{432}{59}\right) = 8^\circ$$

$$g = \text{perditance} = 0$$

$$\sigma = \operatorname{arc} t g \left[\frac{\sin 2\, b\, x}{\sin h\, 2\, a\, x}\right] = \operatorname{arc} t g \left[\frac{0.565}{0.87}\right] = 79^\circ\ 40'$$

We find therefore the following auxiliary angles:

$$\psi = \sigma - \gamma = 71^\circ\ 40' \text{ and } \Sigma = \psi - \phi_1 = 48^\circ\ 10'$$
$$\Sigma = \sigma + \gamma = 87^\circ\ 40' \text{ and } X = \Sigma + \phi_1 = 111^\circ\ 10'$$

and finally,

$$\varepsilon = \operatorname{arc} (t g\, h y p\, a x\, t g\, b x) = \operatorname{arc} = 30^\circ\ 20'$$

Resulting vectors at beginning of line, transmitting tension at the end:

$$U_1 = 86{,}700 \text{ volts.} \qquad I_1 = 167 \text{ amperes, } 5$$

The star tension at the beginning of the line corresponding to

$$U_1 = U_0 = \alpha\, U_1 = 86.700 \times 0.825 = 71{,}500 \text{ volts}$$

The tension drop produced by the distributing current is

$$V_s = 366 \times 0.572 \times 167.5 = 35{,}000 \text{ volts}$$

The angle δ of the tension U_0 and of the tension at the beginning of the line is given by:

$$tg\,\delta = \frac{V_0 \sin \Sigma}{V_0 + U_0 \cos \Sigma} = 0.274 \qquad \delta = 15^\circ\ 20'$$

The star tension at the beginning of the line is therefore $U_0' = \dfrac{V_0 \sin \Sigma}{\sin \delta} =$ 98,500 volts and the tension between the wires is 170,500 volts. The current at the beginning, corresponding to that of the terminal point of the line is likewise:

$$I_0 = \alpha I_1 = 0.825 \times 167.5 = 138.5 \text{ amperes.}$$

The charging current at no load is:

$$J_0 = \frac{\beta}{m} U_1 = \frac{0.572}{366} \times 86{,}700 = 135 \text{ amperes}$$

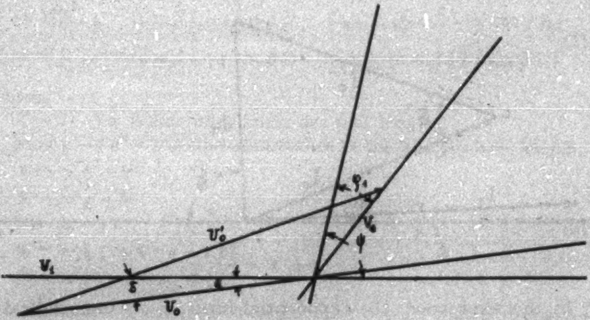

FIG. 4

On the other hand, we have:

$$tg\,\delta' = \frac{J_0 \sin X}{I_0 + J_0 \cos X} = 197\ \delta' = 54^\circ$$

The total resulting current at the beginning of the line is therefore:

$$J_0' = \frac{J_0 \sin X}{\sin \delta'} = 154.5 \text{ amperes.}$$

The power-factor at the generator end is $\cos \phi_0 = 0.90$.

Fig. 4 and 5 give the diagrams of the tensions and currents. We might note that a similar construction could be made for any value of x, that is to say for any point of the line.

This method would be quite simple, if all the hyperbolic functions were eliminated. To do this, their development in series might be made use of as has been done. This, however, introduces an approximation in the results.

Instead of maintaining the hyperbolic functions or their development in series, they may be easily transformed as follows:

$$\alpha - \sqrt{\frac{\cos h\, 2\, a\, x + \cos 2\, b\, x}{2}}$$

If we introduce into this, the value of cos hy. $2\, a\, x$ we easily find:

$$\alpha^2 = \frac{e^{4ax} + 1 + 2\, e^{2ax} \cos 2\, b\, x}{4\, e^{2ax}}$$

and finally,

$$\alpha = \sqrt{\frac{(e^{2ax} + \cos 2\, b\, x)^2 + \sin^2 2\, b\, x}{4\, e^{2ax}}}$$

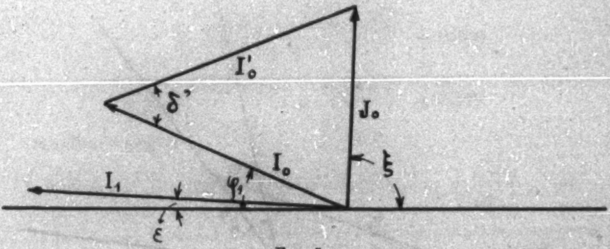

Fig. 5

In this expression, the exponential function e^{2ax} may be calculated without any difficulty. Moreover, this expression suggests a simple graphical method to determine the value of α if the exponential curve $Y = e^x$ has first been drawn in short limits of the value of x.

In the same way, we have:

$$\beta = \sqrt{\frac{(e^{2ax} - \cos 2\, b\, x)^2 + \sin^2 2\, b\, x}{4\, e^{2ax}}}$$

and

$$t\,g\,\sigma = \frac{2\, e^{2ax}}{e^{4ax} - 1} \sin 2\, b\, x$$

In these expressions the hyperbolic functions have disappeared.

Charles P. Steinmetz (by letter): With the very long high-voltage transmission lines that are now being considered, it is not safe to calculate the performance of the line by the approximate equations that have been used for the lines of moderate voltage and moderate length; but the numerical calculations should be made by using the complete equations of the transmission line, or at least the approximate calculations should be checked in a number of points by the exact equations. Although the complete equations of the transmission line appear complicated on first sight, numerical calculations can be made easily and rapidly by a systematic arrangement in tabulated form. However, even with 60-cycle lines several hundred miles long, satisfactory accuracy can still be derived by the approximation of substituting for the exponential functions of the complete equations the first terms of their series. The calculation is essentially simplified thereby.

I. Investigation

The voltage $\underset{\cdot}{E}$ and current $\underset{\cdot}{I}$ at any point l of the transmission line is given, in the usual representation by complex quantities, by the equations.*

$$\begin{aligned} \underset{\cdot}{I} &= Y\{\underset{\cdot}{C}_1\, \varepsilon^{+\alpha l} (\cos \beta l - j \sin \beta l) - \underset{\cdot}{C}_2\, \varepsilon^{-\alpha l} (\cos \beta l + j \sin \beta l)\} \\ \underset{\cdot}{E} &= V\{\underset{\cdot}{C}_1\, \varepsilon^{+\alpha l} (\cos \beta l - j \sin \beta l) + \underset{\cdot}{C}_2\, \varepsilon^{-\alpha l} (\cos \beta l + j \sin \beta l)\} \end{aligned} \tag{1}$$

where:

$Z = r - j x$ = line impedance per unit length,

$Y = g - j b$ = shunted admittance of the line per unit length,

$$\begin{aligned} z &= \sqrt{r^2 + x^2} \\ y &= \sqrt{g^2 + b^2} \\ V &= \alpha - j \beta \\ \alpha &= \sqrt{\tfrac{1}{2} (z y + r g - x b)} \\ \beta &= \sqrt{\tfrac{1}{2} (z y - r g + x b)} \end{aligned} \tag{2}$$

the distance l is counted towards rising power; that is, from the receiving end towards the generator, and $\underset{\cdot}{C}_1$ and $\underset{\cdot}{C}_2$ are integration constants.

Choosing as unit length the entire line, $l = 0$ gives $\underset{\cdot}{I}_0$ and $\underset{\cdot}{E}_0$ at the receiving end, and $l = 1$ gives $\underset{\cdot}{I}_1$ and $\underset{\cdot}{E}_1$ at the generator end of the line, and Z is the total impedance, $\dot{Y}$ the total shunted admittance of the entire line.

Neglecting the shunted conductance; that is, assuming the power consumed by leakage and electrostatic losses in the line as negligible compared with that consumed by the effective line resistance r—as is always done—gives:

$$\begin{aligned} \alpha &= \sqrt{\tfrac{1}{2} b (z - x)} \\ \beta &= \sqrt{\tfrac{1}{2} b (z + x)} \\ Y &= - j b \end{aligned} \tag{3}$$

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* *Transient Phenomena.* Section III, Par. 8, equations (21)

Substituting now into equations (1) the values:

$$V\underset{\cdot}{C}_1 = \underset{\cdot}{A}_1$$

$$V\underset{\cdot}{C}_2 = \underset{\cdot}{A}_2 \qquad (4)$$

$$\frac{V}{Y} = Z_0 = r_0 + j\,x_0$$

where, by (2) and (3):

$$r_0 = \frac{\beta}{b}$$

$$x_0 = \frac{\alpha}{b} \qquad (5)$$

and denoting:

$$Z_0\underset{\cdot}{I} = \underset{\cdot}{U} \qquad (6)$$

it is:

$$\underset{\cdot}{E} = \underset{\cdot}{A}_1\,\varepsilon^{+\alpha l}\,(\cos\beta\,l - j\sin\beta\,l) + \underset{\cdot}{A}_2\,\varepsilon^{-\alpha l}\,(\cos\beta\,l + j\sin\beta\,l)$$

$$\underset{\cdot}{U} = \underset{\cdot}{A}_1\,\varepsilon^{+\alpha l}\,(\cos\beta\,l - j\sin\beta\,l) - \underset{\cdot}{A}_2\,\varepsilon^{-\alpha l}\,(\cos\beta\,l + j\sin\beta\,l) \qquad (7)$$

If then $\underset{\cdot}{E}_0$ and $\underset{\cdot}{I}_0$ denote voltage and current at the receiving end, for $l = 0$, and $\underset{\cdot}{E}_1$ and $\underset{\cdot}{I}_1$ denote voltage and current at the generator end, for $l = 1$, and:

$$Z_0\underset{\cdot}{I}_0 = \underset{\cdot}{U}_0$$

$$Z_0\underset{\cdot}{I}_1 = \underset{\cdot}{U}_1 \qquad (8)$$

equations (7) give:

Receiving end: $l = 0$,

$$\underset{\cdot}{E}_0 = \underset{\cdot}{A}_1 + \underset{\cdot}{A}_2$$

$$\underset{\cdot}{U}_0 = \underset{\cdot}{A}_1 - \underset{\cdot}{A}_2 \qquad (9)$$

Generator end: $l = 1$,

$$\underset{\cdot}{E}_1 = \underset{\cdot}{A}_1\,\varepsilon^{+\alpha}\,(\cos\beta - j\sin\beta) + \underset{\cdot}{A}_2\,\varepsilon^{-\alpha}\,(\cos\beta + j\sin\beta)$$

$$\underset{\cdot}{U}_1 = \underset{\cdot}{A}_1\,\varepsilon^{+\alpha}\,(\cos\beta - j\sin\beta) - \underset{\cdot}{A}_2\,\varepsilon^{-\alpha}\,(\cos\beta + j\sin\beta) \qquad (10)$$

Since α is a small quantity even in very long lines, because in equation (3), b is small at 25 cycles, while $(z - x)$ is small at 60 cycles, $\varepsilon^{\pm\alpha}$ can be replaced by the first terms of its series:

$$\varepsilon^{\pm\alpha} = 1 \pm \alpha + \frac{\alpha^2}{3} \pm \frac{\alpha^3}{6} + \frac{\alpha^4}{24} \pm \dots \qquad (11)$$

that is, by:

$$\varepsilon^{\pm\alpha} = 1 \pm \alpha \tag{12}$$

or, if a greater accuracy is desired, by:

$$\varepsilon^{\pm\alpha} = 1 + \frac{\alpha^2}{2} \pm \alpha \tag{13}$$

Substituting (13) into (10), rearranging, and then substituting (9), gives:

$$\begin{aligned} \underset{\cdot}{E}_1 &= \underset{\cdot}{E}_0 \, (a_1 - j\, a_2) + \underset{\cdot}{U}_0 \, (c_1 - j\, c_2) \\ \underset{\cdot}{U}_1 &= \underset{\cdot}{U}_0 \, (a_1 - j\, a_2) + \underset{\cdot}{E}_0 \, (c_1 - j\, c_2) \end{aligned} \tag{14}$$

where:

$$\begin{aligned} a_1 - j\, a_2 &= \left(1 + \frac{\alpha^2}{2}\right) \cos\beta - j\, \alpha \sin\beta \\ c_1 - j\, c_2 &= \alpha \cos\beta - j\left(1 + \frac{\alpha^2}{2} \sin\beta\right) \end{aligned} \tag{15}$$

are line constants, independent of voltage, current, and power-factor.

Substituting (8) into (14) gives:

$$\begin{aligned} \underset{\cdot}{E}_1 &= \underset{\cdot}{E}_0 \, (a_1 - j\, a_2) + \underset{\cdot}{I}_0 \, (b_1 - j\, b_2) \\ \underset{\cdot}{I}_1 &= \underset{\cdot}{I}_0 \, (a_1 - j\, a_2) + \underset{\cdot}{E}_0 \, (d_1 - j\, d_2) \end{aligned} \tag{16}$$

where:

$$\begin{aligned} b_1 - j\, b_2 &= Z_0 \, (c_1 - j\, c_2) \\ d_1 - j\, d_2 &= \frac{c_1 - j\, c_2}{Z_0} \end{aligned} \tag{17}$$

hence, by (4), (5), and (15):

$$\begin{aligned} b_1 - j\, b_2 &= \frac{(\beta + j\,\alpha)\left(\alpha\cos\beta - j\left(1 + \frac{\alpha^2}{2}\right)\sin\beta\right)}{b} \\ &= \frac{\alpha\left(\beta\cos\beta + \left(1 + \frac{\alpha^2}{2}\right)\sin\beta\right) - j\left(\beta\left(1 + \frac{\alpha^2}{2}\right)\sin\beta - \alpha^2\cos\right)}{b} \end{aligned} \tag{18}$$

$$d_1 - j\,d_2 = \frac{b\left\{\alpha\cos\beta - j\left(1+\frac{\alpha^2}{2}\right)\sin\beta\right\}}{\beta + j\,\alpha}$$

$$= \frac{b\,(\beta - j\,\alpha)\left\{\alpha\cos\beta - j\left(1+\frac{\alpha^2}{2}\right)\sin\beta\right\}}{\beta^2+\alpha^2}$$

and as by (3):

$$\beta^2 + \alpha^2 = b\,z$$

it is: (19)

$$d_1 - j\,d_2 = \frac{\alpha\left(\beta\cos\beta - \left(1+\frac{\alpha^2}{2}\right)\sin\beta\right) - j\left(\beta\left(1+\frac{\alpha^2}{2}\right)\sin\beta + \alpha^2\cos\beta\right)}{z}$$

Thus, if:

e_0 = voltage at the receiving end of line,

i_0 = total current, consisting of the power current i_0' and the reactive current i_0'' (counted positive for lag), that is:

$$\underset{\cdot}{I}_0 = i_0' + j\,i_0''$$

voltage and current at the generator end of the line are given by the equations (16) as:

$$\begin{aligned} \underset{\cdot}{E}_1 &= e_0\,(a_1 - j\,a_2) + (i_0' + j\,i_0'')\,(b_1 - j\,b_2) \\ \underset{\cdot}{I}_1 &= (i_0' + j\,i_0'')\,(a_1 - j\,a_2) + e_0\,(d_1 - j\,d_2) \end{aligned} \qquad (20)$$

If in equations (1) the sign of l is reversed, the distance is counted toward rising power; that is, $l = 0$ gives generator voltage and current, e_1 and i_1, $l = 1$ gives receiving voltage and current, e_0 and i_0. The only change resulting herefrom is a reversal of the sign of α and β in equations (10) and (15), and thus a change of the sign of the second terms of (16) and (20):

$$\begin{aligned} \underset{\cdot}{E}_0 &= e_1\,(a_1 - j\,a_2) - (i_1' + j\,i_1'')\,(b_1 - j\,b_2) \\ \underset{\cdot}{I}_0 &= (i_1' + j\,i_2')\,(a_1 - j\,a_2) - e_1\,(d_1 - j\,d_2) \end{aligned} \qquad (21)$$

II. CONCLUSIONS

In a long-distance transmission line, voltage $\underset{\cdot}{E}_1$, current $\underset{\cdot}{I}_1$, and power-factor at the generator end can be accurately calculated from the voltage $\underset{\cdot}{E}_0$, current $\underset{\cdot}{I}_0$ and power-factor at the receiving end, and inversely, by the simple equations:

1. Generator voltage:

$$\underset{\cdot}{E}_1 = e_0 (a_1 - j\, a_2) + (i_0' + j\, i_0'')\, (b_1 - j\, b_2)$$

Generator current:

$$\underset{\cdot}{I}_1 = (i_0' + j\, i_0'')\, (a_1 - j\, a_2) + e_0 (d_1 - j\, d_2) \qquad (22)$$

where:

e_0 = voltage,
i_0' = power current,
i_0'' = reactive current at receiving end of line.

2. Receiver voltage:

$$E_0 = e_1 (a_1 - j\, a_2) - (i_1' + j\, i_2' (b_1 - j\, b_2)$$

Receiver current:

$$\underset{\cdot}{I}_0 = (i_1' + j\, i_1'')\, (a_1 - j\, a_2) - e_1 (d_1 - j\, d_2) \qquad (23)$$

where:

e_1 = voltage,
i_1' = power current,
i_1'' = reactive current at generator end of line, and:

$a_1 - j\, a_2$; $b_1 - j\, b_2$; $d_1 - j\, d_2$ are line constants, which are calculated once for all, and then permit the calculation of the performance of the line under all conditions of voltage, load and power-factor, from above equations (22) and (23).

These line constants are:

$$a_1 - j\, a_2 = \left(1 + \frac{\alpha^2}{2}\right) \cos \beta^\circ - j\, \alpha \sin \beta^\circ \qquad (15)$$

$$b_1 - j b_2 = \frac{\alpha \left(\beta \cos \beta^\circ + \left(1 + \frac{\alpha^2}{2}\right) \sin \beta^\circ\right) - j \left(\beta \left(1 + \frac{\alpha^2}{2}\right) \sin \beta^\circ - \alpha^2 \cos \beta^\circ\right)}{b} \qquad (18)$$

$$d_1 - j\, d_2 = \frac{\alpha \left(\beta \cos \beta^\circ - \left(1 + \frac{\alpha^2}{2}\right) \sin \beta^\circ\right) - j \left(\beta \left(1 + \frac{\alpha^2}{2}\right) \sin \beta^\circ + \alpha^2 \cos \beta^\circ\right)}{z} \qquad (19)$$

where:

$$\alpha = \tfrac{1}{2} \sqrt{b\,(z - x)}$$
$$\beta = \tfrac{1}{2} \sqrt{(z + x)} \qquad (24)$$

and in degrees:

$\beta^\circ = 57.3\, \beta$

and:

$$\left.\begin{aligned} r &= \text{resistance,} \\ L &= \text{inductance,} \\ C &= \text{capacity of total line; thus if:} \\ f &= \text{frequency,} \end{aligned}\right\} \qquad (25)$$

$$\left.\begin{aligned} x &= 2\,\pi\, f\, L = \text{line reactance,} \\ b &= 2\,\pi\, f\, C = \text{shunted line susceptance,} \\ z &= r^2 + x^2 \ \ = \text{line impedance.} \end{aligned}\right\} \qquad (26)$$

The possible error of the calculation is of the magnitude $\frac{\alpha^3}{6}$, hence, very small.

III. INSTANCE

As instance may be considered a 180-mile, three-phase transmission line, consisting of three wires No. 000 B. & S. G., 10 ft. between wires, operated at 60 cycles.

The line constants are:

$$r = 180 \times 0.33 = 60 \text{ ohms per line.}$$

$$L = 180\,(0.74 \log \frac{D}{R} + 0.08) = 383 \text{ mh.}$$

(where D = 10 ft. = 120 ins. = distance between conductors, R = 0.205 ins. = radius of conductor.)

$$\begin{aligned} f &= 60 \text{ cycles, hence:} \\ x &= 2\,\pi\, f\, L = 145 \text{ ohms,} \\ z &= r^2 + x^2 = 157 \text{ ohms.} \end{aligned}$$

$$C = 180 \times \frac{0.041}{\log \frac{D}{R}} \text{ mf., hence:}$$

$$b = 2\,\pi\, f\, C = 10^{-3} \text{ mhos.}$$

This gives:

$$\begin{aligned} \alpha &= 0.074 \\ \beta &= 0.389 = 22.3^\circ \end{aligned}$$

and:

$$\begin{aligned} a_1 - j\, a_2 &= 0.928 - 0.028\, j \\ b_1 - j\, b_2 &= (0.055 - 0.143\, j)\ 10^{+3} \\ d_1 - j\, d_2 &= (-0.010 - 0.974\, j)\ 10^{-3} \end{aligned}$$

A. Determine generator voltage, current, and power-factor required to deliver 95,000 volts at non-inductive load.

95 kv. between lines gives $95 \div \sqrt{3} = 55$ kv. per line. Non-inductive load means $i_0'' = 0$.

Thus substituting: $e_0 = 55$, $i_0'' = 0$ into equations (22) gives:

$$\underset{\cdot}{E}_1 = 55\ (0.928 - 0.028j) + i_0'\ (0.055 - 0.143j).$$
$$= (50.9\ - 1.5j)\ + i_0'\ (0.055 - 0.143j)\ \text{kv.}$$
$$\underset{\cdot}{I}_1 = i_0'\ (0.928 - 0.028j) - 55\ (0.010 + 0.974j).$$
$$= i_0\ (.0928 - 0.028j) - \ (0.5 + 53.5j)\ \text{amperes.}$$

Hence, for: $i_0 =$	0	40	80	120	160 amperes
$\underset{\cdot}{E}_1 = e_1' - j\,e_1'' =$	$50.9 - 1.5j$	$53.1 - 7.2j$	$55.3 - 12.9j$	$57.5 - 18.7j$	$59.7 - 24.4j$
$\underset{\cdot}{I}_1 = i_1' - j\,i_1'' =$	$-0.5 - 53.5j$	$36.6 - 54.6j$	$73.7 - 55.7j$	$110.9 - 56.9j$	$140. - 58.j$
hence, absolute:					
$e_1 = \sqrt{e_1'^2 + e_1''^2} =$	50.9	53.6	56.8	60.5	64.5 kv.
$e_1 \sqrt{3} =$	88.3	92.8	98.5	104.8	112.0 kv.
$i_1 = \sqrt{i_1'^2 + i_1''^2}$	53.5	65.6	92.4	125.8	159.0 amp.
Input: $P_1 = e_1' i_1' + e_1'' i_1'' =$	55	2330	4790	7430	10,250 kw.
Apparent input: $Q_1 = e_1 i_1 =$	2720	3520	5260	7610	10,270 kva.
Output: $P_0 = e_0 i_0 =$	0	2200	4400	6600	8,800 kw.
Power-factor: $\frac{P_1}{Q_1} =$	2.0	66.3	91.1	97.6	99.8%
				lag	lead
Efficiency: $\frac{P_0}{P_1} =$	0	94.4	91.8	85.8	88.8%

The possible error of the calculation is of the magnitude:

$$\frac{\alpha^3}{6} = 0.00007, \text{ or } 0.007\%,$$

thus far beyond the accuracy of the numerical calculation.

Generator volts and amperes are plotted in Fig. 1.

B. Determine generator voltage, current and power-factor, required to deliver 95,000 volts at 90 per cent power-factor lag, and at 90 per cent power-factor lead.

$$e_0 = 55$$
$$i_0' = 0.90\ i_0$$
$$i_0'' = \pm 0.44\ i_0$$

Thus:

$$\underset{\cdot}{E}_1 = 55\ (0.928 - 0..28j) + i_0\ (0.90 \pm 0.44j)\ (0.055 - 0.143j)$$

$$= (50.9 - 1.5j) + i_0 \begin{Bmatrix} 0.112 - 0.126j \\ 0.013 - 0.131j \end{Bmatrix} \begin{matrix} \text{lag.} \\ \text{lead.} \end{matrix}$$

$$\underset{\cdot}{I}_1 = i_0\ (0.90 \pm 0.44j)\ (0.928 - 0.028j) - 55\ (0.10 + 0.974j)$$
$$= i_0 \begin{Bmatrix} 0.847 + 0.383j \\ 0.823 - 0.433j \end{Bmatrix} - (0.5 + 53.5j) \begin{matrix} \text{lag.} \\ \text{lead.} \end{matrix}$$

Hence, for: *Lag*:					
$i_0 =$	0	40	80	120	160 amperes
$\underset{\cdot}{I}_0 = i_0' + j\, i_0'' =$	0	$36+17.6j$	$72+35.2j$	$108+52.8j$	$144+70.4j$
$\underset{\cdot}{E}_1 = e_1' - j\, e_1'' =$	$50.9-1.5j$	$55.4-6.5j$	$59.9-11.6j$	$64.3-16.6j$	$68.8-21.7j$
$\underset{\cdot}{I}_1 = i_1' - j\, e_1'' =$	$-0.5-53.5j$	$33.4-38.2j$	$67.3-22.9j$	$101.1-7.5j$	$134+7.8j$
$e_1 = \sqrt{e_1'^2+e_1''^2} =$	50.9	55.8	61.0	66.4	72.1 kv.
$e_1\sqrt{3} =$	88.3	96.8	105.6	115.3	125.0
$i_1 = \sqrt{i_1'^2+i_1''^2} =$	53.5	50.7	71.1	101.4	134.3 amp.
$P_1 = e_1' i_1' + e_1'' i_1'' =$	55	2100	4310	6620	9060 kw.
$Q_1 = e_1 i_1 =$	2720	2830	4340	6730	9690 kva.
$P_0 = e_0 i_0' =$	0	1980	3960	5940	7920 kw.
Power-factor: $\frac{P_1}{Q_1} =$	2.0	74.3	99.3	98.4	93.5%
Efficiency: $\frac{P_0}{P_1} =$	0	94.3	91.9	89.7	87.4%
			lead<———	———>lag	

Lead:					
$i_0 =$	0	40	80	120	160 amperes
$\underset{\cdot}{I}_0 = i_1' - j\, i_0'' =$	0	$36-17.6j$	$72-35.2j$	$108-52.8j$	$144-70.4j$
$\underset{\cdot}{E}_1 = e_1' - j\, e_1'' =$	$50.9-1.5j$	$50.4-6.7j$	$49.9-12j$	$49.3-17.2j$	$48.8-22.5j$
$\underset{\cdot}{I}_1 = i_1' - j\, i_1'' =$	$-0.5-53.5j$	$32.4-70.8j$	$65.3-88.1j$	$98.3-105.5j$	$131.2-122.8j$
$e_1 = \sqrt{e_1'^2+e_1''^2} =$	50.9	50.9	51.3	52.2	53.7 kv.
$e_1\sqrt{3} =$	88.3	88.3	88.9	90.5	93.1 kv.
$i_1 = \sqrt{i_1'^2+i_1''^2} =$	53.5	77.9	109.7	144.2	179.7 amp
$P_1 = e_1' i_1 + e_1' i_1'' =$	55	2110	4320	6650	9180 kw.
$Q_1 = e_1 i_1 =$	2720	3960	5610	7520	9660 kva.
$P_0 = e_0 i_0' =$	0	1980	3960	5940	7920 kw.
Power-factor: $\frac{P_1}{Q_1} =$	2.0	53.3	77.0	88.4	95.0%
Efficiency: $\frac{P_0}{P_1} =$	0	93.8	91.6	89.3	86.3%

Generator volts and amperes are plotted in Fig. 1.

C. Determine voltage, current, and power-factor of receiving circuit, at which maximum power is delivered from a generating station giving 120 amperes at 110,000 volts three phase.

110 kv. between lines gives $e_1 = 110 \div 3 = 63.6$ kv. per line.

Let:

p_1 = power-factor,
g_1 = reactive-factor at generator,

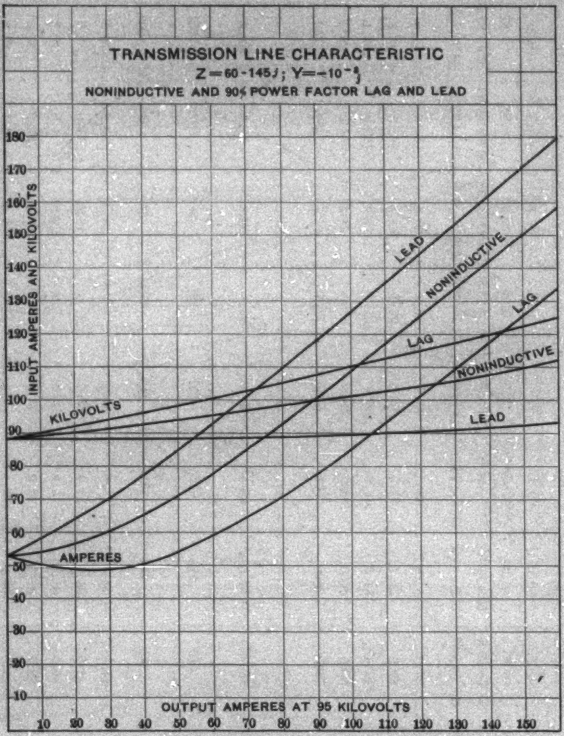

FIG. 1

it is:

$$\underset{\cdot}{I}_1 = i_1' + j\, i_1'' = i_1\,(p_1 + j\, g_1) = 120\,(p_1 + j\, g_1)$$

Hence, by equations (23):

$$\begin{aligned}\underset{\cdot}{E}_0 &= 64.6\,(0.028\,j) - 120\,(p_1 + j\, g_1)\,(0.055 - 0.143j)\\ &= (59.9 - 1.9j) - (6.6 - 17.2j)\,(p_1 + j\, g_1)\\ \underset{\cdot}{I}_0 &= 120\,(p_1 + j\, g_1)\,(0.928 - 0.028j) - 64.6\,(-0.010 - 0.974j)\\ &= (111.4 - 3.4j)\,(p_1 + j\, g_1) + (0.6 + 62.9j)\end{aligned}$$

Hence, for									
e_1 =	+0.5	+0.3	+0.2	+0.1	0	−0.1	−0.2	−0.3	−0.5
p_1 =	0.87	0.95	0.98	0.99	1.00	0.99	0.98	0.95	0.87
$E_0 = e_0' + j e_0''$ =	45.6+9.8j	48.4+12.4j	50+13.7j	51.7+14.4j	53.3+15.3j	55.1+15.8j	56.8+16.3j	56.8+16.4j	62.8+16.4j
$I_0 = i_0' + j i_0''$ =	99.4+116.6j	107.7+93.1	110.6+81.9j	111.7+70.6j	112+59.5j	111.1+48.4j	109.2+37.3j	105.7+26.3j	96.0+3.2j
hence, absolute:									
$e_0 = \sqrt{e_0'^2 + e_0''^2}$ =	46.6	50.0	51.8	53.7	55.5	57.3	59.1	61.0	64.9
$e_0 \sqrt{3}$ =	80.7	86.6	89.7	93.0	96.3	99.2	102.3	105.5	112.3
$i_0 = \sqrt{i_0'^2 + i_0''^2}$ =	153.3	142.4	137.6	132.2	126.8	121.2	115.4	109.0	96.1
$P_0 = e_0' i_0' + e_0'' i_0''$ =	5670	6380	6650	6800	6880	6900	6810	6640	0080
$P_1 = e_1 i_1 p_1$ =	6740	7360	7600	6700	7750	7700	7600	7360	6740
$Q_1 = e_1 i_1$ =	7750								
hence, efficiency:									
$\frac{P_0}{P_1}$ =	84.1	86.7	87.5	88.3	88.8	89.6	90.1	90.7	90.2
$\frac{e_0''}{e_0'}$ = tan E_0 =	.215	.256	.274	.278	.287	.287	.287	.278	.261
$\frac{i_0''}{i_0'}$ = tan I_0 =	1.17	.865	.741	.633	.532	.436	.342	.249	.033
$\measuredangle E_0$ =	12.2	14.4	15.3	15.8	16.0	16.0	16.0	15.8	14.8
$\measuredangle I_0$ =	49.5	41.0	36.6	32.3	28.0	23.6	18.9	14.0	2.0
$\measuredangle \theta_0 = \measuredangle I_0 - \measuredangle E_0$	37.3	26.6	21.3	16.5	12.0	7.6	+2.9	−1.8	−12.8
$p_0 = \cos\theta_0$ =	79.2	89.4	93.1	95.9	97.8	99.1	99.9	99.9	97.6
$q_0 = \sin\theta_0$ =	61.5	44.8	36.3	28.4	20.8	13.2	+5.1	−3.1	−22.2

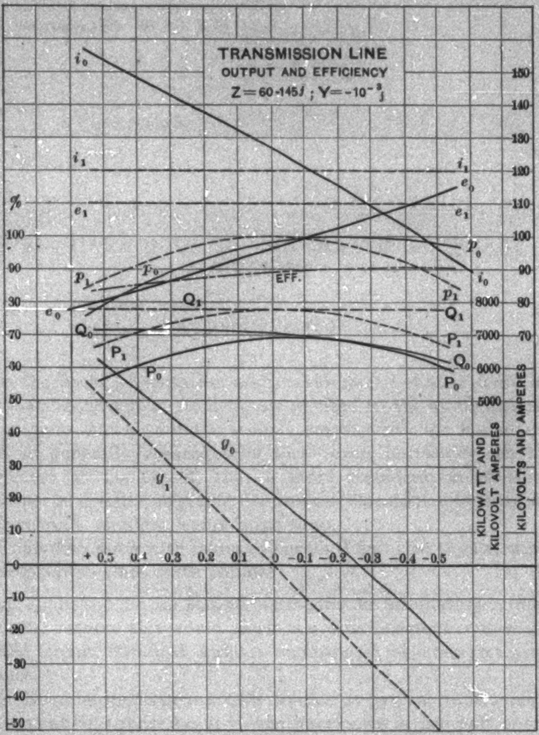

Fig. 2

Volts, amperes, efficiency, power-factor, and reactive-factor are plotted in Fig. 2, with the values at the receiving end in full lines, at the generator end in dotted lines, and the reactive-factors at the generator end of the line as abscissas.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 29, 1909.

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EVEN HARMONICS IN ALTERNATING-CURRENT CIRCUITS

BY JOHN B. TAYLOR

In the usual presentation and consideration of wave-forms in alternating-current circuits we are so used to the mathematical expressions which omit the second, fourth, sixth, etc. harmonics and so generally assume that these even harmonics can be neglected at the outset, that a short consideration of usual and special conditions giving rise to even harmonics in alternating-current circuits, seems opportune.

From discussion with many engineers, I find that the following misconceptions are quite popular:

a. There can be no second harmonics in alternating-current circuits, because this would result in a direct-current component in the circuit, obtained without commutator or other rectifying device.

b. Even harmonics cannot be handled by typical transformers, so that should there be any even harmonics at one part of the circuit these will be in some way suppressed or balanced at the first transformation.

c. Wave-forms of electromotive force from commercial generators do not contain even harmonics, hence nothing can give rise to them later in the system.

No explanation is offered as to why these misconceptions should be so common, and a slight endeavor to get at the root of the notions shows that the average text-book on alternating currents, at some point usually near the introduction, states that windings and poles of commercial generators are symmetrical, so that alternate waves will be of the same shape, and hence have no even harmonics. Little or no reference to even harmonics is made later in such books.

As a matter of fact, the number of transmission systems at this very moment transmitting, with transformers transforming, and receiving apparatus receiving, alternating currents in which the even harmonics are quite as prominent as the odd and al-

FIG. 1.—Record of telephone currents with sustained vowel sounds in transmitter. Upper curve, *u* (as in rude). Middle curve, *a* (as in far). Lower curve, *i* (as in machine). All pitched at *A* 110; that is, the *A* above 8 foot or cello *C*. J. B. Taylor's voice, April 18, 1907. (Time proceeds from left to right.)

together essential to the proper operation of the system—the number of these systems is so much greater than all the lighting, power, and railway plants added together, as to leave no comparison between the figures. By this, reference is made to the number of telephone conversations being carried on at any one time. The wave-form corresponding to speech is very complex if analyzed in the usual method by Fourier's Series, and the accompanying oscillograph records in Fig. 1, which shows current corresponding to simple sustained vowel sounds, will give an idea of the even, as well as odd, harmonics that telephone lines, transformers and receiving apparatus have to deal with.

There is no difficulty in constructing an alternating-current generator to have a wave-form containing considerable even harmonics, when such are desired. There is also no difficulty in connecting standard generators in series or in parallel for example, a 25-cycle generator and a 50-cycle generator, when the resulting wave-form will have pronounced even harmonics.

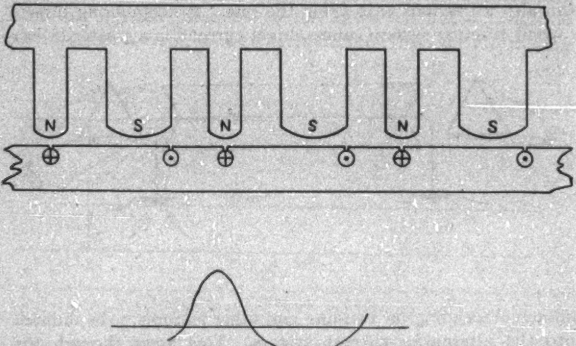

FIG. 2

If an alternating-current generator has a *symmetrical* armature winding and *unsymmetrical* north and south poles, the even harmonics will not appear. If the winding is *unsymmetrical* with the north and south poles *symmetrical*, again the even harmonics will be absent. The combination, however, of an *unsymmetrical* winding with *unsymmetrical* poles, will in general bring out even harmonics. Fig. 2 shows diagrammatically such an alternating-current generator with approximate wave-form due to the special arrangement of winding and the differently shaped north and south poles.

Neglecting the special case of the telephone, of more practical consideration than what has preceded are typical commercial systems in which even harmonics are likely to be introduced and the effect of these harmonics on transformers. The simplest way in which even harmonics may be brought into an alternating-current system is by grounding at more than one point, and these points may be neutral or not. For example, Fig. 3 shows a typical three-phase, high-tension transmission system with transformer neutrals grounded at both ends. Fig. 4 shows the typical single-phase railway with ground at sub-station and also at various cars along the line. A neighboring direct-current traction system causes direct current, in a greater or less amount depending on bonding and other features, to be shunted into the alternating-current system. This flows through the transformer windings giving what I term a "magnetic biased" condition. In other words, there is magnetic flux in the iron of the transformer, apart from excitation derived from alternating-current mains.

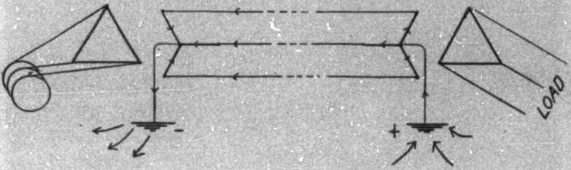

FIG. 3

This shunted or leakage direct current may easily be as much as, or greater than, the exciting current of the transformer, which will give normal or greater magnetic density in the iron, and since many transformers are worked well up toward the saturation point, the iron in the transformer may be nearly saturated before any connection is made with alternating-current supply.

This combination in which transformer iron is initially at a greater magnetic density than is reached in normal alternating-current service, gives a condition which some persons, on superficial consideration, have stated to be equivalent to a heavy overload or short-circuit on the transformer. The argument is, that since the iron is already practically saturated, the normal flux must be added to this saturated condition in order to give the normal counter electromotive force. While such a condition may exist for a very short interval of time when closing the circuit the stable condition is not at all of this nature. The magnetizing current under the conditions described, that is, with direct current in windings of the same order of magnitude as the normal exciting current, does not cause the exciting current to become of the order of a short-circuit current nor even full-load current. This is because the iron, instead of working from the saturated condition as a mean point, works about a mean point not far from zero, and in that portion of a cycle when the flux is in the opposite direction to the initial saturated condition due to direct current, enough extra current from the alternating circuit is supplied practically to neutralize the direct-current ampere-turns. The general effect of this is to increase the exciting current, accompanied by a distortion of the current wave-shape, as shown in the oscillograph record in Fig. 5.

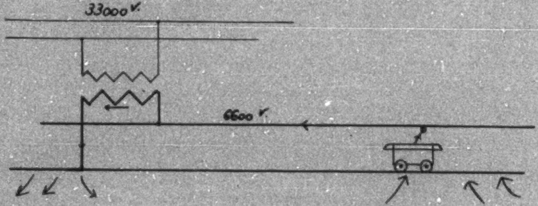

FIG. 4

Roughly, the value of this exciting current, when transformers are magnetically biased, is the value of the normal exciting current added to the direct current. In other words, it may be said that there is a component of the alternating current tending to neutralize the direct-current ampere-turns, and, as another component, the normal exciting current.

If the direct current is in the primary winding and the excitation is from the secondary, or vice versa, the direct current must be multiplied by the ratio of transformation in order to obtain the equivalent direct current for this addition. For example, referring to Fig. 4, the 6600-volt, single-phase trolley wire with sub-station transformer and car as indicated, may have shunted into the winding a current of 5 amperes. The normal exciting current of the sub-station transformer from the 33,000 volt transmission line is, say, 0.5 ampere, but owing to the 5 amperes in the secondary winding, the primary exciting current will become $0.5+\frac{5\times6600}{33000}=1.5$ amperes. There will be some additional losses in transformers carrying direct current, due mainly to increased current density in the winding, and probably a small increase in iron losses due to the unsymmetrical magnetic cycle with maximum flux of one polarity greater than normal.

Fig. 5.—Record showing pronounced second harmonic in transformer magnetizing current due to direct current in windings. Upper curve: electromotive force at terminals from 60-cycle generator. Lower curve: exciting current.

The arrangement of apparatus as shown in Fig. 6, gives a convenient way of introducing direct current into a transformer winding without, at the same time allowing the direct-current circuit to become a load or short-circuit on the transformer. This test requires two transformers, preferably identical, with primaries connected in parallel, and secondaries (with alternating potential balanced) in series with any convenient source of direct current.

In case it is necessary to make such test on a single transformer, a reactance can be introduced in the direct-current circuit to prevent appreciable alternating current from circulating in the direct-current system, or a low-voltage winding on the transformer can be connected through resistance to a high-voltage, direct-current source, such as a 600-volt railway system. If the voltage of the transformer winding is small compared with the direct voltage, the alternating current flowing into the direct-current system will be negligible.

Another combination of apparatus which may introduce direct current in transformer windings, is a synchronous converter connected for Edison three-wire service, the neutral for the three-wire service being derived from connection with transformer neutrals.

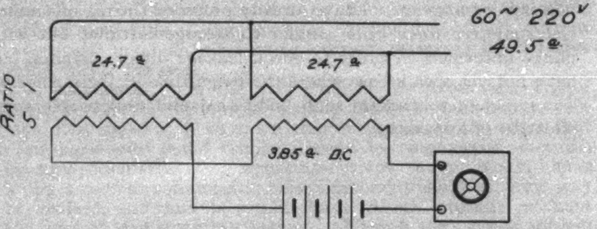

Fig. 6.—Connections for test. 75-kw. transformers. Connected for 50-230 volts. Excited from 220 volt, 60-cycle circuit. Direct current, 3.85 amperes in 1150-volt winding. Normal exciting current at 220 volts, 60-cycles, approximately 5 amperes. Calculated exciting current with direct-current magnetization. (5 x 3.85) + 5 = 24.25 amperes—(Observed value was 24.7 amperes.)

With this combination, the difference between the currents on the two sides of the lighting system passes through transformer windings. If the transformers are "diametrically connected" to the converter, this direct current will divide; and if the resistance of transformer and converter connections are symmetrical from the neutral point, this divided direct current will cause no magnetic flux.

However, with the direct-current neutral derived from star-connected transformers, direct current from the neutral does give a biased magnetic condition in the transformer iron with accompanying increase of transformer exciting current and change in wave-shape, as explained above. Since this current divides among three transformers and its magnitude is not great, unless the lighting system is badly unbalanced, little additional transformer heating is likely to be noticed. Star-connected transformers have been so used with converters for a number of years without serious results, as far as I can learn. However, a diametrical connection seems preferable when laying out a new system.

Conclusion. The practical feature of this discussion is that leakage of direct current into transformer windings—unless these currents are of themselves sufficient to cause considerable additional heating in the windings—will not indirectly cause sufficient increase in the exciting current to cause serious overheating or burn-out. I have already proposed the use of counter electromotive force cells, similar to storage-batteries but with plates unformed, in order to check leakage direct currents, but have not yet seen a case where the magnitude of these currents was sufficient to warrant such additional and undesirable complication of apparatus.

DISCUSSION ON "EVEN HARMONICS IN ALTERNATING-CURRENT CIRCUITS." FRONTENAC, N. Y., JUNE 29, 1909

Frederick Bedell: Confirming the author's conclusions, I have found that a direct current in a transformer increases the iron losses very much less than might be supposed, and also increases the copper losses very much less than might be supposed. The increase in the copper losses is due to two causes: 1. The increase of the exciting component of the alternating current, which is in quadrature with the power component, and so increases the total alternating current by a very small amount. 2. The direct current itself. So far as heating effect is concerned, the direct current behaves as if it were in quadrature with both the power component and the exciting component of the alternating current—the three quantities being mutually in quadrature as though in three dimensions—so that the direct current increases the effective value of the whole current very little. For example, 20 per cent direct current superposed upon an alternating current increases its effective value only 2 per cent.

V. Karapetoff: On the first page of his paper Mr. Taylor refers to certain statements usually made in text-books. He says that there is a common misconception to the effect that even harmonics could not be present in commercial circuits, because otherwise the alternating-current wave would have a direct-current component; this component could in some way be utilized, and thus we would have direct current without the use of commutating devices. I think the whole subject of even harmonics can be understood with reference to the following two simple statements:

1. Let a conductor revolve in an unsymmetrical field, such as is represented in Fig 2, the poles being of different size.

The electromotive force induced at any instant is proportional to the rate at which the flux is cut, or

$$e = \frac{d\,\phi}{d\,t}.$$

Integrating this, gives

$$\phi_1 = \int_0^{t_1} e\,d\,t,$$

where ϕ_1 is the total flux issuing, say, from the north pole, and t the interval of time during which the conductor cuts the lines of force under this pole. Similarly, for the south pole

$$\phi_2 = \int_{t_1}^{t_2} e\,d\,t.$$

But ϕ_1 is always equal to ϕ_2; this is a fundamental law of nature: It is impossible to have a north flux larger or smaller than the corresponding south flux. Hence

$$\int_0^{t_1} e\,d\,t = \int_{t_1}^{t_2} e\,d\,t.$$

With reference to the curve shown in Fig. 2, the above equation means that the area of the curve above the axis of abscissas is always equal to that below the axis, however unsymmetrical the curve itself might be. In practical terms, a direct-current measuring instrument, consisting of a permanent magnet and a moving coil, always shows zero in this case. Therefore, in whichever way the machine is constructed, direct current cannot be obtained from it without the use of a commutator or an electrical valve. (Who of us in our younger years did not attempt to invent a direct-current generator without a commutator!) The above simple equation or rather the fundamental law $\phi_1 = \phi_2$ shows why this is impossible.

2. When more than one conductor is connected in series, the conductors must be spaced unsymmetrically in order to preserve even harmonics, provided such harmonics are induced in each individual conductor. Indeed, with reference to the curve in Fig. 2, let two conductors, in which such electromotive forces are induced, be spaced by 180 electrical degrees and connected in series. To find the resultant electromotive force, a second curve must be drawn, inverted, and shifted through 180°. It will be easily seen that the resultant curve has identical half-waves, and all the even harmonics are cancelled. But if the shift is different from 180°, some of the even harmonics can be preserved.

Since in practice armature conductors are spaced symmetrically, the statement remains true that no even harmonics are present in ordinary commercial circuits.

By suitably spacing the conductors, odd harmonics may be cancelled, instead of even ones. Thus, by shifting conductors through 120° and connecting them in series, the third harmonic is abolished, while the second, fourth, etc., are preserved to some extent, provided they are induced by an unsymmetrical field in each individual conductor.

Chas. F. Scott: Some years ago when synchronous converters were first used with a middle wire, in the way familiar to all, the two-phase converter was employed and the middle point was brought out from the middle of the transformer winding, which served as a balance coil. That was a simple matter. When the problem came to use star-connected coils on three-phase circuits, it seemed at first that a peculiar and unbalanced condition would result and the direct current would magnetize the cores independently, and the neutral point might go floating about in some peculiar way, the transformers probably behaving quite badly. We were surprised on making a test to find how well the apparatus did behave, although the alternating-current transformers were treated with large amounts of the direct current. In such cases, however, the magnetizing current is in general small compared with the normal current, hence a large magnetizing current may not greatly increase the total current. In other cases, however, this direct current may lead to disturbances which are considerable. In one case with which I had to do some time ago, involving transformers which had little or no output but were depended on for their voltage relations, it happened that there was considerable resistance in the primary circuit, but this ordinarily had but little effect as the flow of magnetizing current was very small. When, however, direct current flowed in the secondary circuit, then the magnetizing current was increased many times, which caused an undue drop in the primary resistance, and did affect the operation of the apparatus.

The curve shown in Fig. 5 is of interest, as it shows the peculiar form of the magnetizing current which has to do double the duty of counteracting the direct current and of producing its own magnetization.

Charles P. Steinmetz: Regarding the statement of the author, confirmed by Dr. Bedell, that the iron loss in the unsymmetrical cycle produced by the existence of second harmonics resulting from direct current, is not seriously increased. I made some investigations on the subject 18 years ago, which were published in the A.I.E.E. PROCEEDINGS of 1892, in the second paper on the law of hysteresis. There the conclusions are that at the same difference between the limits of flux density the hysteresis loss is the same regardless as to whether the cycles are symmetrical or between unsymmetrical limits. There would thus be no increase in iron losses. The unsymmetrical cycles, which I investigated, were relatively small, and the accuracy was not so great. There may have been smaller differences which would have escaped notice, but they certainly prove that there is no serious increase of hysteresis loss in the unsymmetrical cycle over the symmetrical cycle, with the same distance between the limits of flux density. The eddy-current loss, however, is probably increased by the greater abruptness of the change.

It is also interesting to realize that even harmonics are practically as frequent as odd harmonics in the transient phenomena of alternating-current circuits.

As to the discussion of the origin of even harmonics, the usual statement that they cannot exist is misleading. The correct statement is that the *constant term*, which is the first term of even harmonics, cannot exist in a machine without commutating or rectifying devices, whether symmetrical or unsymmetrical arrangements are used; but the further terms of the even harmonics, from the second upward, can exist; there is no physical reason why they should not exist, but owing to constructive conditions, they are practically always absent.

J. B. Taylor: I do not think there is anything to rebut in the discussion. Professor Karapetoff possibly misunderstood a reference to the text-books. The books themselves are not in error, but hazy ideas of even harmonics exist in the minds of many engineers, and the treatment in the text-books has been rather meagre, which possibly accounts for the misconceptions.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 29, 1909.

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THE RESISTANCE AND REACTANCE OF ARMORED CABLES*

BY J. B. WHITEHEAD

It has been asserted frequently that no form of iron protective covering is permissible for single conductors carrying alternating currents. Experience and simple calculation show this assertion to be well founded with regard to even the thinnest walls, if such walls form a completely closed magnetic circuit about the conductor. In a recent single-phase railway installation it was necessary to carry the trolley circuit across a drawbridge and the nature of the traffic through the draw rendered it advisable to armor the cables, several of which were to be installed for reserve and emergency. Obviously, the use of single-conductor, steel-armored cables was permissible if the reactance and losses in the armor were not prohibitive. There being an apparent absence of data on the subject, and some opinion adverse to the use of such cables, the values of reactance were calculated as explained below. The results showed that even at 60 cycles, and with outgoing and return cables placed close together, the reactance would not be serious; and the subsequent measurements indicate that in cables as manufactured the effect is considerably less than the calculated value, so that for purposes similar to that mentioned the use of the cables is entirely practical.

Calculation. The usual cable consists of a central stranded conductor, surrounded by rubber or paper insulation, covered by tape, lead, jute, and armor in the order named. The armor consists of a number of wires spiralled around the cable; the number of armor wires varies somewhat with the size of cable but is not usually less than 20. The pitch of the spiral is from 5 to 10 times the diameter of the cable, being fixed by the size of armor wire and the requirement to cover the entire outer surface. The exact expression for the inductance in the armor wires is too unwieldly for direct evaluation. A close approximation to its value may be had by neglecting the spiral, by assuming that the intensity of magnetic force is uniform through the armor and equal to the value at the center of the section of an armor wire, and by assuming that the lines of magnetic intensity are circles concentric about the center of the main conductor.

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* The measurements were made at the Johns Hopkins University. The cables were loaned by the Standard Underground Cable Company.

It is obvious that any increase in the inductance due to the armor will take place almost entirely in the region near the circle passing through the lines of contact between the armor wires. This is borne out by the form of integral which is involved, which shows that 0.8 of the total induction is within an arc of 10 degrees on each side the point of contact, and indicates that the above assumptions yield results only a few per cent greater than the exact value. The problem then resolves itself into a determination of the reluctance of a closed magnetic circuit formed by a number of iron wires placed side by side on the circumference of a circle, the magnetic field being at right angles with the length of the wires. The magnetic field is circular and of uniform intensity in the space occupied by the wires. The approximate calculation is further simplified without serious error if the circle of armor wires be considered as laid out side by side in the plane of a uniform magnetic field.

Consider the reluctance of an elementary portion of the magnetic circuit at a distance x from the line passing through all the points of contact, of a width dx, and length equal to the diameter of the armor wire. The length of path in iron is $2\sqrt{r^2 - x^2}$, and the length in air is $2\,(r - \sqrt{r^2 - x^2})$, r being the radius of the armor wire cross-section. The total reluctance per unit length of cable of the circular element of thickness dx is then

$$R = \frac{2\,n}{d\,x}\left(\frac{\sqrt{r^2 - x^2}}{\mu} + r - \sqrt{r^2 - x^2}\right)$$

in which n is the number of armor wires and μ the permeability. The error in neglecting the curvature of the circle of contacts is rom 1 to 2 per cent for 20 to 30 armor wires.

The total flux in the armor alone is

$$\Phi_i = \frac{4\,\pi\,i}{10\,n} \cdot \tfrac{1}{2} \int_{-r}^{+r} \frac{dx}{r+a\,\sqrt{r^2-x^2}}$$

$$= \frac{0.4\,\pi\,i}{n} \cdot \frac{1}{a} \left\{ \frac{\pi}{2} - \frac{2}{\sqrt{1-a^2}} \tan^{-1} \left(\frac{1-a}{1+a} \right) \right\},$$

in which

$$a = \frac{1-\mu}{\mu}$$

For $\mu = \;50,\ \Phi_i = 13.8\ \frac{0.4\,\pi\,i}{n}$

$$\mu = 300,\ \Phi_i = 36.7\ \frac{0.4\,\mu\,i}{n}$$

If there were no armor wire the total magnetic induction in the corresponding air space would be equal to

$$\frac{0.4\,\pi\,i}{n};$$

consequently the presence of the armor increases the induction in the space occupied by it from 14 to 36 times, according to the value of μ.

The effect of the flux in the armor on the total inductance of the cable will depend on the radius of the central conductor and the distance between it and the return conductor; that is, on the proportion of the total field of force which is occupied by the armor. The data of one of the cables on which measurements were made are as follows:

Single conductor 0 B. & S. gauge; stranded $\frac{8}{32}$ in. of paper, $\frac{1}{8}$ in. of lead, and a jute bedding about $\frac{1}{8}$ in. thick, armored with No. 10 (B. W. G.) steel wires.

Diameter over strand	373	mils.
" over paper insulation	873	"
Diameter over lead sheath	1123	"
Outside diameter, approximate	1500	"

The values of the inductance of this cable per mile of conductor, at different distances, d, between ajacent surfaces of parallel cables, assuming the permeability of the armor to be 1, and applying the formula

$$L = \frac{161}{10^8}\left\{2 \log \frac{D}{r} + \frac{1}{2}\right\},$$

are as follows:

D = distance between centers of cables
$d = 0$, $L = 0.75$ millihenry
$d = 2$ in., $L = 1.02$ millihenrys
$d = 6$ in., $L = 1.26$ "
$d = 12$ in., $L = 1.45$ "

The value of L for the space inside the armor is 0.69. Consequently the difference, 0.06, between 0.75 and 0.69 is the proportion which is increased by the factors 14 to 36 mentioned above. Calling this factor k, the values of L with armor wires in contact over the entire circumference are got by adding $0.078\ (k - 1)$ to the values given above. For $k = 36$ the values of L are increased by the armor 3.8, 3.1, 2.7, and 2.5 times respectively for the distances of separation given above, and for 6 ft. separation the factor is 2.1. That is, depending on the distance of separation the reactance of the usual single-conductor, steel-armored cable may be from two to four times as great as the reactance of the same cable without steel armor. Obviously the reactance constitutes no objection to the use of such cables in moderate lengths.

The losses in the armor are not subject to simple calculation. As already stated, about 80 per cent of the total induction in the armor is within an arc of 10 degrees on each side of the point of contact of two adjacent wires. For $\mu = 300$ this means an average value of the induction B equal to $166\ H$ within a wall from 0.03 to 0.05 in. thick. At 100 amperes the value of H in the armor of the type of cable under discussion is about 10. It is evident that the resulting losses would not rise to any great value. It is also evident that the assumption that the armor wires are all in contact throughout their length will not be true of the manufactured product. Since the induction in the armor will be greatly decreased for any appreciable air-gap between the individual wires, the reactance and losses should fall below the approximate values as calculated. This conclusion was borne out by the following measurements.

Single-conductor, iron-armored cable. The description of this cable has been already given. The measurements were made on two lengths each 51 ft. long, at different distances apart, with frequencies of 25 and 60 cycles and various values of current. The quantities measured were current, impedance, resistance, and power. The instruments employed were a voltmeter with a range of 0.5 to 3.5 volts and a scale which could be read to 0.005 volt, an electrodynamometer, and a wattmeter. The wattmeter was connected in the 110-volt primary circuit of a special transformer which gave low secondary voltages. The primary current of this transformer was also measured. The net loss in the cable as given in the accompanying table is the wattmeter reading minus the aggregate of the iron and copper losses in the transformer and the copper loss in the leads to the cable. Separate determinations of these values were made at each reading, and the actual or dead resistance—resistance with direct current flowing—measured after each alternating-current reading. The results are given in Table I.

The increase in the impedance with current and with distance between cables is evident but not great. At 60 cycles it varies from 2.2 times the dead resistance, at 67 amperes with the cables close together, to 2.8 times the resistance at 90 amperes with 12 in. between cables. The effective resistance as calculated from the watts lost in the cable is given in column 9 and the effective reactance in column 10. The decrease in effective resistance and the increase in effective reactance with increasing separation is noticeable at 60 cycles, but not important at 25 cycles. At the lower frequency, owing to the saturation of the transformer, the accuracy of the figures for the losses is somewhat impaired. This is reflected in the value of the reactance which is the square root of the difference between two squares of approximately equal value. The order of magnitude, however, is sufficiently indicated.

The reactance per mile of two cables 12 in. apart, as measured at 60 cycles and 90 amperes, is 2.13 ohms; the value calculated as previously explained is 2.73; at 25 cycles the values are 0.80 and 1.14, respectively. The figures for other distances of separation show similar differences, and indicate the measured values to be about 70 per cent of those calculated for the ideal case. As already stated, this is accounted for by the fact that the armor wires are not in contact at all points.

The effective resistance increases with the current density but varies very little with the distance of separation. The value in the cable here investigated increased at 60 cycles and a current density of 1 ampere per 1000 circular mils, to about twice the dead resistance.

TABLE I.

SINGLE-CONDUCTOR CABLE WITH IRON ARMOR.

Two parallel lengths, 51 ft. long each. Conductor No. 0 B. & S. Stranded Armor 29 No. 10 B.W.G. Wires.

	Frequency 60 cycles.								
1 Separation of cables, inches	2 Amperes	3 Volts	4 Impedance	5 Resistance	6 Gross watts	7 Trans. loss watts	8 Net loss in cable watts	9 Effective Resistance	10 Effective Reactance
0	67.2	1.50	0.0223	0.0104	245	160	85	0.0188	0.012
	75.4	1.75	0.0232	0.0104	305	198	107	0.0188	0.0135
	88	2.14	0.0242	0.0105	415	265	150	0.0199	0.0144
2	60.8	1.37	0.0225	0.0102	197	135	62	0.0167	0.0151
	76.28	1.86	0.0244	0.0104	315	208	107	0.0184	0.016
	87.4	2.22	0.0254	0.0103	418	261	157	0.0205	0.0156
6	60.6	1.45	0.0239	0.0103	197	137	60	0.0165	0.0173
	76.25	1.95	0.0255	0.0103	316	212	104	0.0179	0.0181
	86.7	2.31	0.0267	0.0101	411	269	142	0.0189	0.0188
12	59.8	1.49	0.0249	0.0105	196	137	59	0.1064	0.0187
	68.5	1.8	0.0263	0.0104	257	178	79	0.0168	0.020
	89.4	2.53	0.0283	0.0104	447	289	158	0.0192	0.021
	Frequency 25 cycles.								
0	68.7	1.05	0.0153	0.0103	245	173	72	0.1152	0.002
	74.3	1.65	0.0157	0.0103	285	202	83	0.0150	0.003
	84.0	1.375	0.0164	0.0103	381	268	113	0.016	0.003
2	69.6	1.085	0.0156	0.0103	246	175	71	0.0146	0.005
	75.6	1.205	0.0159	0.0102	302	213	89	0.0155	0.004
	83.6	1.375	0.0164	0.0103	371	263	108	0.0155	0.005
6	68.3	1.075	0.0157	0.0103	241	173	68	0.0146	0.005
	75.4	1.220	0.0161	0.0102	294	209	85	0.0150	0.006
	85.8	1.48	0.0172	0.0103	417	296	121	0.0164	0.005
12	70.3	1.17	0.0166	0.0104	258	185	73	0.0147	0.007
	75.5	1.275	0.0169	0.0104	313	220	93	0.0163	0.004
	84.1	1.475	0.0175	0.0104	390	279	111	0.0157	0.008

The effect on the impedance of connecting the lead sheathing at both ends and also connecting the iron armor at both ends, with 12 in. separation, is shown in Table II. It is noticeable that the impedance is reduced by each of these secondary circuits. The increase in impedance with increasing current is less marked, however, indicating the low value of reactance resulting from the presence of the closed secondary circuits. In the same table several values of impedance are given for the case of the return current in the lead sheath. A small value of reactance is indicated at 60 cycles, about one-fifth the value of the dead resistance, assuming the effective resistance to be no greater than the dead resistance. At 25 cycles the difference between impedance and dead resistance is so small as to approach the limits of accuracy to which the instruments could be read.

TABLE II.

TWO SINGLE-CONDUCTOR CABLES WITH IRON ARMOR, 12 IN. APART.
Lead sheathings connected at both ends.

60 cycles.				25 cycles.			
Current	Volts	Imped.	Resist.	Current	Volts	Imped.	Resist.
67.5	1.62	0.0240	0.0103	....	....	....	....
77.0	1.89	0.0245	0.0103	80.5	1.375	0.0171	0.0104
84.7	2.1	0.0248	0.0103	90.2	1.59	0.0176	....
Both Sheathings and Armors Connected at Both Ends.							
72.5	1.57	0.0216	0.0105	....	....	....	....
82.7	1.817	0.0219	....	82.1	1.351	0.0164	....
88.6	1.945	0.0219	....	93.7	1.57	0.0167	0.0106
One Cable, with Lead Sheath as Return.							
82.0	1.54	0.0188	0.0185	73.1	1.365	0.0187	0.0187
87.6	1.645	0.0188	0.0186	78.7	1.48	0.0188	0.0188
93.0	1.775	0.0191	0.0187	82.0	1.54	0.0188	0.0188

Single-conductor, copper-armored cable. A series of measurements were made on two 48-ft. lengths of cable similar in all respects to that with steel armor, except that the armor consisted of 24 No. 8 B. & S. hard-drawn copper wires. The impedance was measured at different current densities and with different separations of the cables, with the copper armor connected and disconnected at the ends. The impedance was also measured for a return circuit through the armor wire. The results are given in Table III.

TABLE III.

Single-Conductor Cables with Copper Armor.

	Armor Open				Armor Connected at ends.			
Separation	Cur.	Volts	Imped.	Resist.	Cur.	Volts	Imped.	Resist.
60 cycles.								
0	84.7	0.92	0.0108	0.0092	87.8	0.98	0.0111	0.0092
	91.8	1.01	0.011	0.0092	....	....	....	....
2 in.	84.0	1.00	0.0119	0.0093	82.6	1.03	0.0124	0.0093
	87.7	1.05	0.0120	0.0094	....	....	....	....
6 in.	80.0	1.055	0.0132	0.0094	77.5	1.06	0.0137	0.0094
	86.4	1.152	0.0133	0.0094	84.1	1.16	0.0138	0.0094
12 in.	77.1	1.11	0.0144	0.0096				
	84.6	1.24	0.0146	0.0096				
25 cycles.								
0	98.8	0.83	0.0095	0.0093	89.0	0.845	0.0095	0.0091
2 in.	87.5	0.855	0.0098	0.0094	86.2	0.86	0.0099	0.0093
6 in.	86.9	0.897	0.0103	0.0094	87.2	0.92	0.0105	0.0094
12 in.	85.1	0.905	0.0106	0.0097	83.5	0.935	0.0112	0.0096

One cable length with return through copper armor.

60 cycles.				25 cycles.			
Current	Bolts	Imped.	Resist.	Current	Volts	Imped.	Resist
71.6	0.500	0.0070	0.0065	65.0	0.42	0.0064	....
83.6	0.595	0.0071	0.0067	71.6	0.48	0.0067	0.0066
89.5	0.6530	0.0070	0.0068	73.5	0.50	0.0068	....

At 60 cycles and 12 in. separation the reactance per mile of double conductor, as calculated from the measured values of impedance and resistance at 82 amperes is 1.19 ohms. As calculated from the value of L given by the formula previously stated, the value is 1.1. This indicates an appreciable eddy-current loss in the copper armor. The readings with the armors of the two cables connected at both ends indicate a small increase in the effective resistance.

Table IV gives the impedance values for a double-conductor, steel-armored cable. The conductors were similar to those in the single-conductor cables and spaced at 0.873 in. between centres. The diameter over the lead sheath was 2.025 in. and the armor consisted of 38 No. 18 B.W.G. steel wires. At 91 amperes and 60 cycles the impedance per mile, as measured, was 1.14 ohms. The value as calculated by means of the formula for L and the measured value of the dead resistance was 1.09 ohms. The difference between measured and calculated values indicates that the increase in impedance of the double-conductor cable also is due to increase in the effective resistance. This increase is probably due to eddy currents in the lead sheath rather than to any effect of the steel armor.

TABLE IV.

Double-Conductor Cable with Iron Armor.

60 cycles				25 cycles.			
Current	Volts	Imped.	Resist.	Current	Volts	Imped.	Resist.
84.6	0.968	0.0113	0.0101	82.9	0.860	0.0104	0.0101
88.5	1.020	.0115	0.0101	86.0	0.905	0.0105	0.0102
91.0	1.050	0.0115	0.0101				

Conclusions. 1. Theoretically the reactance of the usual type of single-conductor, iron-armored power cable may be from 2 to 4 times that of unarmored cable, depending on the distance to return conductor; the factor increases with decreasing distance.

2. In cables as manufactured the reactance is about 0.7 of the maximum theoretical value.

3. The effective resistance as measured varies little with the distance to return conductor and is about 1.6 and 2 times the

dead resistance at 25 and 60 cycles, respectively, and a current density of 1 ampere per 1000 circular mils.

4. The impedance for distances under 12 in. is about 3 times the dead resistance at 60 cycles and 1.7 to 2 times the dead resistance at 25 cycles. With the sheathing and the armor grounded at both ends the impedance is somewhat lessened and is largely of the nature of resistance.

5. The impedance of a double-conductor, iron-armored cable, with conductors located 0.873 in. apart between centers, and at the current density given above, is about 5 per cent greater at 60 cycles and 3 per cent greater at 25 cycles than the calculated value. The increase is in effective resistance, due to eddy currents in the lead sheathing.

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LOSSES, INDUCED VOLTS AND AMPERES IN ARMOR AND LEAD COVER OF CABLES

BY H. W. FISHER

Part I of this paper is supplementary to the paper by Professor Whitehead, because the data presented were obtained from measurements made on the same cables prior to Professor Whitehead's tests. The results given cover conditions mostly not considered by Professor Whitehead. Any differences in impedance and losses presented are undoubtedly due to the coiling and uncoiling and shipment of cables, as these would tend to change the relative air-gaps between the armor wires. Slight differences may also have been caused by small differences in the lengths of the cables tested, or by differences in temperature.

Professor Whitehead shows clearly how the maximum possible inductance of armored cables can be calculated. His comparison between the calculated and measured impedances is extremely interesting and instructive. It is evident that the impedances of iron-armored, single-conductor cables cannot be calculated with any degree of certainty, because slight differences in the air-gaps between the armor wires materially affect the inductances of the cable. Moreover the induced volts and amperes are also affected by the same cause, hence the results given here for the iron-armored, single-conductor cable must be considered only approximate in their general application to iron-armored cables.

The first cable considered will be the first one mentioned in Professor Whitehead's paper; namely, single conductor No. 0 B. & S. G., insulated with $\frac{8}{32}$ in. paper over which is $\frac{1}{8}$ in. of lead with the usual jute bedding and No. 10 B. W. G. steel wires. The dimensions are as follows:

Diameter over copper strand, = 373 mils.
Diameter over paper insulation, = 873 mils.
Diameter over lead sheath, = 1123 mils.
Outside diameter, approximate, = 1500 mils.
Resistance of conductor per 2000 ft. = 0.21
Resistance of lead sheath per 2000 ft. = 0.53
Resistance of armor per 2000 ft. = 0.35

The following symbols are used to designate the different curves shown in Figs. 1 and 2:

A indicates that the distance between centers of cables was 1.5 in.
B " " " " " " " " " 9 in.
C " " " " " " " " " 24 in.

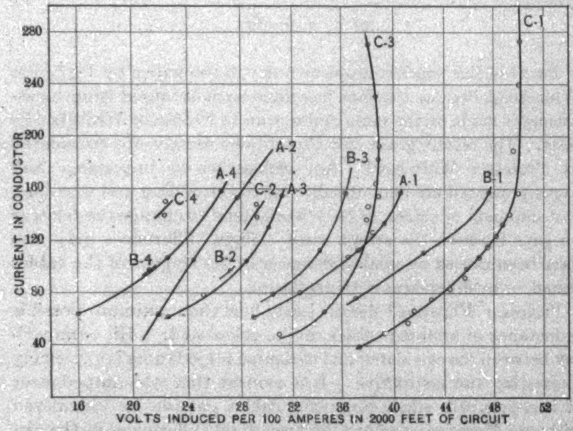

FIG. 1.

The figures used in connection with the above letters indicate the following:

1. Induced current or volts in lead.
2. Induced current or volts in lead, the armor being short-circuited at each end of the cable.
3. Induced current or volts in armor,
4. Induced current or volts in armor, the lead being short-circuited at each end of the cable.
5. Induced current in armor and lead, connected in parallel.

Fig. 1 gives the volts induced per 100 amperes in 2000 ft. of circuit. The reason for expressing the volts in terms of 100 amperes in the conductor is to give at sight a general idea of what pressure might be expected with a current somewhat near that used in practice. It will be seen that the induced volts are greatest when the conductors are farthest apart and when the armor is not short-circuited. Under these conditions, with a normal load of about 170 amperes the induced volts for 2000 ft. of circuit would be about 85. For the same load, a minimum in-

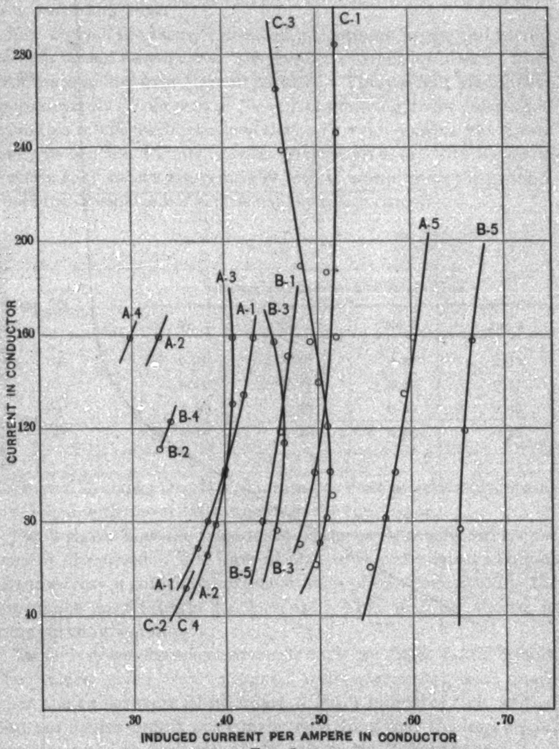

Fig. 2.

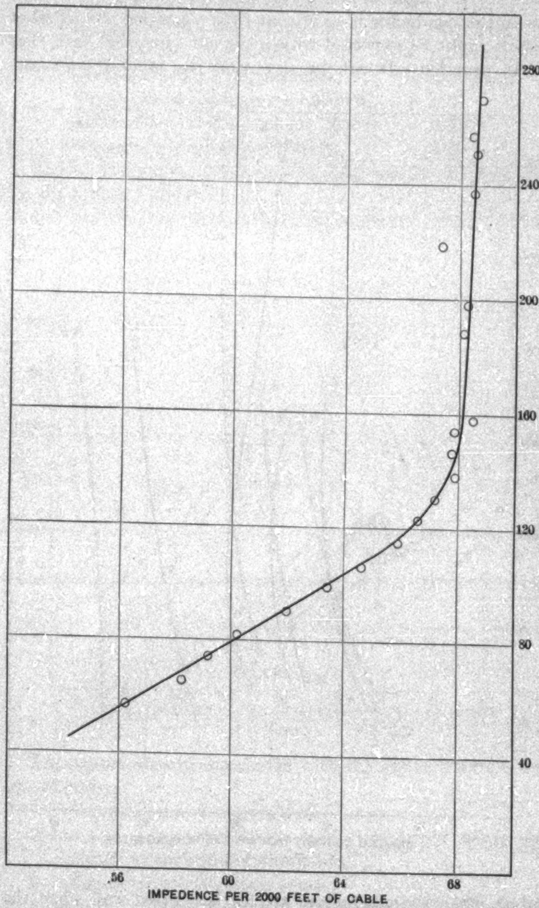

FIG. 3.—Current in conductor

duced electromotive force of 40 volts was obtained on the armor when the lead covers were connected at both ends of the cable. Between these extremes will be found various curves giving the different induced volts corresponding to the various tests that were made. The bends in the curves are characteristic of all circuits containing iron.

Fig. 2 gives the current induced per ampere in the conductor. Here, as would be expected, the greatest current is obtained when both the lead and armor are in parallel. This current amounts to approximately 65 per cent of the current flowing in the conductor. From this it will readily be seen that an armored cable has a tendency to become warmer than an unarmored cable. However, in practice such cables are generally laid in water or in the ground, where the dissipation of heat is readily taken care of.

TABLE I.

Current in conductor	Effective resistance per 2000 ft. of circuit			
	No. 1	No. 2	No. 3	No. 4
60	0.33	0.36	0.36	0.35
100	0.41	0.41	0.40	0.37
160	0.46	0.45	0.44	0.40
240	——	0.48	0.48	0.42

Curve *C*-3 shows that a maximum per cent of induced current is reached with about 100 amperes in the conductor.

Fig. 3 shows how the impedance of the cable is affected by the amount of current. The knee of the curve commences at about 120 amperes; if sufficient current were applied, undoubtedly the impedance would begin to decrease. This will be shown in some curves given later.

Table I gives the effective resistance per 2000 ft. of circuit. The values given were obtained from wattmeter tests made when the cables were 24 in. apart. No. 1 indicates that neither lead nor armor circuit was connected; No. 2 that the lead circuit was connected at each end of the cable; No. 3 that the armor circuit was connected at each end of the cable; No. 4 that both circuits were connected. The conductor resistance to direct current was 0.21 ohms, so it will be seen that the maximum total ap-
loss is somewhat greater than double the conductor loss. W
the distance between centers was 1.5 in. the losses in th

column were increased by about 1 per cent. In the Nos. 2, 3, and 4 columns, the losses were less as the distances were decreased. At 1.5 in. separation and with 60 amperes in the conductor, the difference was slight. With 160 amperes the decrease was about 5 per cent.

It will also be seen that the relative losses given in column 1 increase with the amount of current. For any particular current the losses in the several columns are not materially different, but this condition would not necessarily always be the case.

Single-conductor, copper-armored cable. This cable was made up substantially in the same manner as the first mentioned cable, except that the armor consisted of 24 No. 8 B. & S. G., hard-drawn copper wires.

Table II gives the volts induced in 2000 ft. of circuit per 100 amperes. Comparing this table with the curves in Fig. 1, a marked diminution in induced volts is shown.

TABLE II.

VOLTS INDUCED IN 2000 FT. OF CIRCUIT PER 100 AMPERES

Distance between centers	Measured induced volts	
	In lead circuit	In armor circuit
3 in.	8.2	6.6
6 in.	11	9.5
12 in.	14.3	12.6
18 in.	16.2	14.5

Table III gives the current induced per 100 amperes in the conductor. These tables do not call for comment, except that the induced voltage and current are proportional to the current in the conductor.

TABLE III.

CURRENT INDUCED PER 100 AMPERES IN CONDUCTOR

Distance between centers	Measured induced current	
	In lead circuit	In armor circuit
3 in.	14	44
6 in.	18	56
12 in.	23	63
[illegible]	25	67

Table IV gives the impedance per 2000 ft. of cable for different distances with different connections of armor and lead. The calculated values are also given. In making these calculations it was necessary to estimate the resistance of the lead and armor circuits. The calculated values in the table are not so close as they would have been had the resistance referred to been accurately measured. The formulas for making these calculations were worked out after the cables had been discarded. The most interesting part of this table is that the impedance is greater when the lead circuit is connected at both ends of the cable than when the lead covers are not connected. This seems so contrary to what would be expected that I asked my chief assistant, Mr. R. W. Atkinson, to investigate the subject mathematically. In Part III of this paper will be found his graphical and mathematical solution of this problem; this solution shows the conditions under which the impedance of the cable may be greater when the lead covers are short-circuited.

TABLE IV
IMPEDANCE PER 2000 FT. OF CABLE

Distance between centers	Measured impedance				Calculated impedance	
	Lead and armor free	Leads connected	Armor connected	Both connected	Lead connected	Armor connected
1.5 in.	——	——	——	——	0.234	0.239
3 in.	0.245	0.255	0.252	0.253	0.262	0.262
6 in.	0.264	0.277	0.264	0.262	0.290	0.276
12 in.	0.288	0.304	0.273	0.271	0.321	0.284
18 in.	0.298	0.319	0.276	0.273	0.339	0.283

PART II.

This part deals with tests made on 100-ft. of steel-tape-armored cable of the following construction:

Size of conductor	No. 0 B. & S. G.
Thickness of paper	$\frac{6}{32}$ in.
Thickness of lead	$\frac{1}{8}$ in.
Diameter over lead	$1\frac{1}{8}$ in.
Diameter over armor	$1\frac{5}{8}$ in.
Dimensions of steel tape	0.039 in by 1.5 in.

Two such tapes were applied in the same direction, overlapping each other.

Resistance of conductor	0.0103 ohm.
Resistance of lead sheath	0.0300 “
Resistance of armor	0.150 “

To designate the different curves, the following letters and figures were employed.

A indicates that the cables were 1⅞ in. between centers.

C indicates that the cables were 24 in. “ “

1 indicates induced current or volts in lead.

2 indicates induced current or volts in lead, the armor being short-circuited at each end of the cable.

3 indicates induced current or volts in armor,

4 indicates induced current or volts in armor, the lead being short-circuited at each end of the cable.

5 indicates induced current in armor and lead connected in parallel.

6 indicates lead or armor of each cable not connected nor inter-connected.

7 indicates lead short-circuited at each end of the cable, armor free.

8 indicates armor short-circuited at each end of the cable, lead free.

9 indicates lead and armor short-circuited at each end of the cable.

On account of the continuity of the steel armor, which forms almost a closed magnetic circuit, the curves for this cable are radically different from those of the steel-wire-armored cables.

On referring to Fig. 4, which gives the impedance per 2000 ft. at 60 cycles, it will be seen that the impedances are greatest when the armor and lead are not connected and that a sharply defined maximum is reached with a conductor current of about 80 amperes. There is not much difference in curves A_6 and C_6 except at low current densities, where the greater distance between cables of test C_6 makes the air effect larger proportionally, and hence causes a greater difference of impedance between the two curves.

Short-circuiting the armor at each end of the cable (See A_8 and C_8) decreases the impedance only slightly. However, when both lead and armor are short-circuited (See A_9 and C_9) the impedance is very much reduced and only varies slightly with the amount of current in the conductor. In this kind of cable when the lead and armor are disconnected, the impedance may be 13 times the ohmic resistance. When the lead and armor are short-circuited, which is generally the case in practice, the impedance may be about 3.5 times the ohmic resistance. With larger conductor cables these ratios may be very much increased.

Fig. 5 gives the equivalent resistance per 2000 ft. of circuit. Here a current of about 60 amperes in the conductor seems to produce the maximum resistance. This resistance seems to be virtually independent of the distance between the centers of the cables. It is also striking that curves C_6 and A_6 cross curves C_9 and A_9 at points corresponding to about 40 and 200 amperes respectively, so that for small current densities and very large current densities the equivalent resistance per 2000 ft. of circuit may be less when the lead and armor are not connected than when they are connected. The maximum equivalent resistance is about 8 times the ohmic resistance when the lead and armor are disconnected. Under practical conditions of operation the equivalent resistance would be about 3.5 times the ohmic resistance.

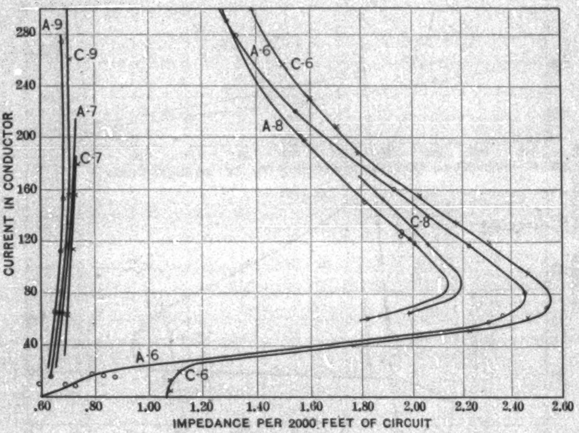

Fig. 4.

All this tends to show how advisable it is to use multiple-conductor cables all under one armor instead of single-conductor armored cables. The equivalent resistances given in Fig. 5 were found by means of wattmeter tests.

Fig. 6 gives the volts induced per 100 amperes in 2000 ft. of circuit. These curves show clearly a maximum rate of induced voltage that corresponds to about 80 amperes in the conductor. As might be expected, the induced voltage is greatest when the cables are farthest apart. At the maximum point the volts per 100 amperes are about 240, or actually about 190 volts. With a load of 170 amperes, the induced volts would be about 290. When the lead is short-circuited the electromotive force on the armor as given by C_4 is very small. The intermediate curves are in the order that one would expect.

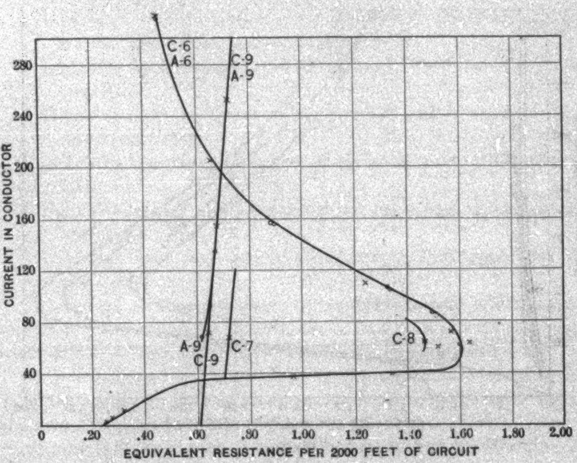

Fig. 5.

The significant fact brought out by these tests is that it is necessary to bond the armor and lead of single-conductor cables like the above, or else arcs may occur betwen the cables, or alternating-current electrolysis may tend to destroy the armor or lead. Even when such cables are laid in water, it would be best to bond the armor and lead occasionally.

Fig. 7 gives the induced current per ampere in conductor. With high current densities the induced current amounts to nearly 85 per cent of the total current. On account of the high resistance of the armor, the current induced therein is small,

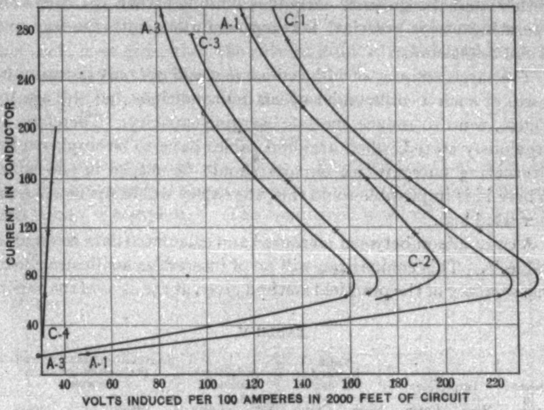
CURRENT IN CONDUCTOR
280
240
200
160
120
80
40
A-3
A-1
C-1
C-3
C-2
C-4
A-3
A-1
40
60
80
100
120
140
160
180
200
220
VOLTS INDUCED PER 100 AMPERES IN 2000 FEET OF CIRCUIT

Fig. 6.

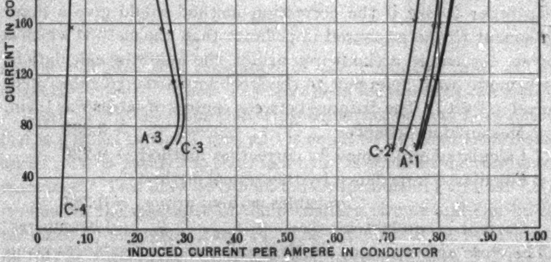
CURRENT IN CONDUCTOR
280
240
200
160
120
80
40
A-5
C-5
C-1
A-3
C-3
C-2
A-1
C-4
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
INDUCED CURRENT PER AMPERE IN CONDUCTOR

Fig. 7.

(See A_3, C_3 and C_4). The other curves are practically close together, and the greatest current is obtained when the cables are operating under practical working conditions with the lead and armor connected.

The large amount of induced current will not only increase the losses of such a cable under operating conditions, but will also, of course, tend to reduce the safe carrying capacity. Therefore, as previously stated, when armored cables have to be employed for alternating currents, all circuits should be placed in one cable. Where it is impossible to do this, the cables will be operated at an increased loss.

A comparison between measured and calculated data is found in Table V. This comparison will be of interest as an illustration of the accuracy of the practical method given at the close of the paper.

TABLE V

Current in conductor	Impedance		Volts induced on lead		Effective resistance		Induced current in lead in per cent of conductor current	
	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
300	0.73	0.716	128	126		0.68	0.815	0.83
156	0.72	0.73	187	187		0.716	0.80	0.87
70	—	—	—	—	0.72	—	—	—

In Table V, the impedances and effective resistances are for lead covers short-circuited at each end of the cable. The values given in Table V are per 2000 ft. of circuit. Only one test was made of effective resistance and that with 70 amperes in the conductor.

In order to see if the correction method would give a closer agreement to the measured impedance than the method which is correct for cables without iron armor, the following calculations were made with reference to the steel-wire-armored cable mentioned in Part I. The distance between centers of cables was 1.5 in.

Measured impedance = 0.233
Calculated impedance by correction method = 0.226
Calculated impedance by theoretical method for cables without armor = 0.283
Current in conductor = 140 amperes.

The close agreement of the first and second impedances given shows that the correction method should be used in connection with armored cables.

Comparison calculations between the two methods as applied to the steel-tape-armored cable show a fairly close agreement. This agreement is no doubt due to the fact that the reactance of this cable is so great that the current induced in the lead forms a large part of the conductor current, and a large change in the reactance will only slightly affect the lead current.

PART III.

Calculation of impedance, etc. A graphical method may be used for determining the conditions existing when the armor or lead circuit is completed. The conditions required to be known are the reactance and resistance of the conductor and of the secondary circuit. These may have been measured or calculated.

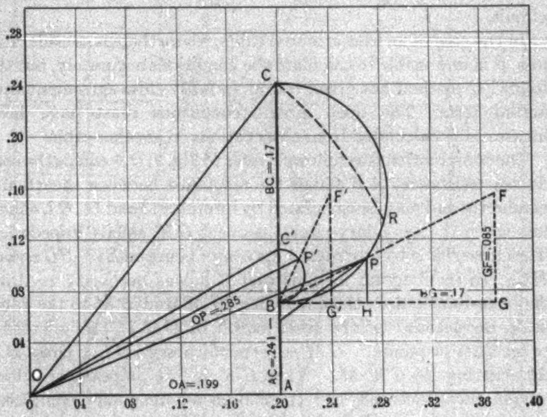

FIG. 8.

Refer to Fig. 8. The following construction has been made. OA is parallel to the X axis and is equal to the conductor resistance. AC is parallel to the Y axis and is equal to the conductor reactance. This may be culculated by formulas 11 and 14. BC is equal to the reactance of the secondary circuit and can be determined by formulas 12 and 14. The circle CPB has been drawn on CB as a diameter. BG has been drawn equal to BC, the reactance of the secondary circuit, and GF equal to r, the resistance of same. BF cuts the circle CPB at the point P.

Then OP is the impedance of the conductor when the secondary circuit is closed, OC being the impedance when this circuit is open. As r is varied, the locus of the point P is on the semicircle CPB; and it may readily be seen that the impedance may be greater with the sheath connected than when it is open. The effective resistance is $OA + BH$, the effective reactance $AB + HP$. BF is the impedance of the secondary circuit; the current induced in it per ampere in conductor (see formula 7) is equal to $CB \div BF$. If there be another secondary circuit beneath, whose reactance is CI, the voltage induced in it is equal to IP. If the current coil of a wattmeter be in series with the main conductor and the volt coil be connected to the terminals of this circuit, the reading will be the watts lost in the closed secondary circuit.

In the case of an iron-armored cable, where there is considerable loss, it is impossible to calculate the conditions accurately, but the following method has given results in fairly close agreement with actual tests. The open circuit conditions must have been measured or calculated from observations on another cable.

The construction is as follows: (refer to Fig. 9) OA equals the conductor resistance; AB equals the reactance between sheath and conductor and may be calculated by formulas 13 and 14. OL equals loss when the secondary circuit is open; OK equals impedance. The circle BKC is constructed, its center being on BC. BG equals BC. In the diagram as constructed it was necessary to draw BG one-fourth size, thus reducing GM and BM to the same scale, on account of the great length of GM. This affects no other lines or points. GM is perpendicular to OL. Draw BKM, cutting MG in M. Then OK is the impedance which would have resulted had there been an imaginary completed circuit of reactance BC and resistance GM surrounding the conductor so as to have a reactance between itself and the conductor are equal to AB.

This assumption is actually far from true. A large part of the loss, probably one-half or more, in the tape-armored cable is due to hysteresis. The excuse for the method is that errors in calculations based on it are less than the variations would be between two cables made to the same specifications. For the remainder of the calculation consider this imaginary circuit in parallel with the sheath when the latter is connected. The point P may be located as before, OP being the impedance of the cable. The voltage induced in the lead on open circuit is BK. The current is determined as before, except that the whole current (equals $CB + BF$) may be supposed to divide between the two in accordance with the resistances.

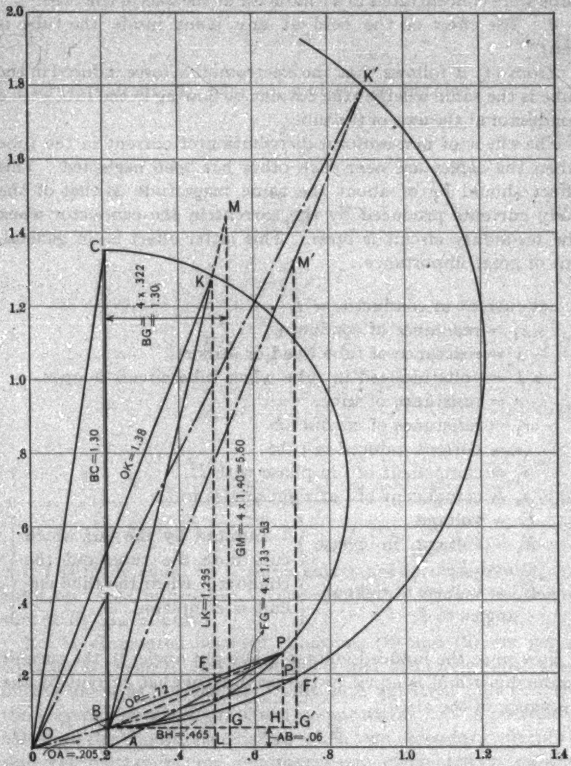
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
.2
.4
.6
.8
1.0
1.2
1.4
K′
M
C
K
M′
BG = 4 x .322 = 1.30
BC=1.30
OK=1.38
LK=1.235
GM=4 x 1.40=5.60
FG=4 x 1.33=.53
P
F
P′
F′
B
OP=.72
G
H
G′
O
A
BH=.465
L
AB=.06
OA=.205

FIG. 9.

It may be noted that the accuracy of any method] for [calculation of the performance of an iron-armored cable is somewhat reduced, due to the fact that the reactance voltage caused by the iron is far from a sine wave.

In demonstrating the correctness of the construction for the cable without iron the following facts are made use of.

1. The effect on the magnetic field of current flowing in a tube, is the same, at any point outside the tube, as if the current in the tube were concentrated in a conductor at the axis of the tube.*

2. The effect on the field at any point inside the tube is zero.*

From (1) it follows that the electromotive force induced in the tube is the same whether the current be flowing in the tube or in a conductor at the axis of the tube.

The effect of non-uniform distribution of current in the tube when the cables are near each other has been neglected. This effect should be of about the same magnitude as that of the eddy currents produced by the current in the conductor when the secondary circuit is open. This latter effect is, in general, not of great importance.

Let current in conductor $= I$.
$x + x_1$ = reactance of conductor,
x = reactance of tube (lead or armor).
$x I$ = volts induced in tube when tube circuit is open.
r = resistance of tube,
r_1 = resistance of conductor.
i = current induced in tube.
i_1 = component of i in phase with I.
i_2 = component of i at right angles to I.
E = voltage.
E_1 = voltage in phase with I.
E_2 = voltage at right anangles to I.

{ Induced by the flux which cuts both the tube and the conductor when the tube circuit is completed. }

Now since the induced voltage is at right angles to the current producing it and is equal to the product of that current by the reactance of the circuit,

$$E_1 = i_2 x \qquad (1)$$

$$E_2 = (I - i_1) x \qquad (2)$$

Then since E_1 and E_2 are the voltages induced in the tube by the combined action of the current in the conductor and in the tube itself, the current induced is equal to the voltage divided by the resistance, and is in phase with the voltage producing it, or

---

* See Maxwell, Third Edition, Vol. II, page 316.

$$i_1 = \frac{E_1}{r} \tag{3}$$

$$i_2 = \frac{E_2}{r} \tag{4}$$

From equations (1), (2), (3), and (4) we obtain:

$$i_1 = \frac{x^2}{r^2+x^2} I \tag{5}$$

$$i_2 = \frac{x\,r}{r^2+x^2} I \tag{6}$$

$$i = \frac{x}{r^2+x^2} I \tag{7}$$

$$E = \frac{x^2\,r}{r^2+x^2} I \tag{8}$$

$$E_2 = \frac{x\,r^2}{r^2+x^2} I \tag{9}$$

$$\frac{E_1}{E_2} = \frac{x}{r} \tag{10}$$

If I is made equal to 1, these values are in ohms, volts, and amperes. The impedance of the conductor equals the vector sum of E_1, E_2, x, and r.

If r be eliminated between equations (8) and (9), we get an equation between E_1 and E_2, which is that of a circle constructed on the line x as a diameter. This with equation (10) confirms the correctness of the graphical construction. It is possible to calculate the conditions existing when two secondary circuits of different reactances and resistances are connected in parallel, but the formula is very complicated and is of the fourth degree. It is much simpler and generally would be very closely approximate to assume a single circuit having a reactance of about the average of the two. This will always give values of the total loss somewhat lower than the true loss.

Having given the performance of one armored cable with the secondary circuits open, that of another of different dimensions may be easily determined almost as closely as one of the same dimensions, provided only that the size of the armor and the method of construction be the same.

Let a_1 = diameter through the center of the armor of the measured cable, a_2 = same diameter on the cable whose performance it is desired to calculate at a current = I. Then the loss of apparent power in the second cable at I amperes caused by the armor is equal to $\frac{a_2}{a_1}$ times that of the first at $I\,\frac{a_1}{a_2}$ amperes. The loss to be used in the calculation is the total loss in the cable less the conductor $I^2\,r$. To get the impedance due to the armor, subtract from the total impedance (vectorially) the conductor resistance and the reactance calculated for cables of the same size at the same separation without armor. More accurately, that part of the reactance which is produced by the space that would be occupied by the armor should not be subtracted. Neglecting this will make an error of about 5 per cent in the reactance.

The formulas used to obtain calculated results given in this paper are as follows:

Inductance of a cable:

$$L = l\,\frac{15.24 + 140.5 \log 10 \frac{d}{r}}{10^9} \tag{11}$$

l = length of cable in feet.
d = distance between centers and
r = radius of conductor.

$$\text{For tubes—inductance} = l\,\frac{140.5 \log_{10} \frac{d}{r}}{10^9} = L \tag{12}$$

This is strictly true only for an infinitely thin tube. Inductance of a circuit consisting of a tube and solid conductor

$$= L = l\,\frac{15.24 + 140.5 \log_{10} \frac{r_1}{r}}{10^9} \tag{13}$$

r_1 being the radius of the tube.

The reactance = $2\,\pi\,f\,L$ (14)

Where f = the frequency.

In Fig. 8 the construction resulting in the determination of the impedance $O\,P$ was for the 1/0 copper armored cable, distance between centers being 18 in. The impedance $O\,P'$ is that of the same cable, the distance between centers being 1.5 in. Both these impedances were determined with the armor short-circuited at each end of the cable.

The construction of Fig. 9 is based on a conductor current of 300 amperes and 24 in. between centers of the steel-tape armored cable. The incompleted semicircle $B\,F'\,K'$ is the construction for 156 amperes. It is interesting to note the relative increase of reactance compared with ohmic resistance, which is much greater in Fig. 9 than in Fig. 8.

DISCUSSION ON "LOSSES, INDUCED VOLTS AND AMPERES IN ARMOR AND LEAD COVER OF CABLES." FRONTENAC, N. Y. JUNE 29, 1909.

Ralph D. Mershon: Once I asked Mr. Fisher to make some measurements on three-conductor, three-phase cables, measurements which would show whether there were any losses in the lead sheath. I knew of a case where some three-conductor cables showed after installation higher losses and higher drops than the calculations had indicated. I do not remember the results of these measurements and it will be interesting to hear them in connection with this paper.

H. W. Fisher: I made tests to determine the lead and copper losses due to eddy currents in a piece of 500,000 cir. mils lead-covered cable. First of all, the total losses were measured and the $I^2 R$ losses subtracted to get the total eddy-current losses. Then the lead cover was removed and the same test repeated to obtain the eddy-current losses in the conductor. The frequency was 60 cycles. The total eddy-current loss was 13 per cent of the $I^2 R$ loss, and was divided as follows; lead loss 6 per cent; copper loss 7 per cent.

John B. Whitehead: Mr. Fisher has spoken of the advisability of putting all the conductors into one sheath wherever it is possible. There is one class of circuit—an instance of which led to the paper which I gave this morning—in which there is necessity for insulating only one side, the case of a single-phase trolley carried through a drawbridge. It is unnecessary to insulate the grounded conductor. Double-conductor cables cost 50 per cent more, and by putting in single-conductor cables more may be put in for the same money and additional reserve capacity obtained. The reactance of short lengths is no difficulty, nor are the losses great enough to cause trouble.

Charles P. Steinmetz: This paper brings out strongly the fact that in steel-armored, single-conductor cables we may get heating and effective resistance and impedance many times greater than these corresponding to the conductor copper. It also brings out the fact that the increase of effective resistance and impedance cannot be expressed in any simple manner, but varies over an enormous range for changes of current with changes of arrangement, with the manner and character of applying the steel armor, etc. Incidentally, this impedance curve of the cable has a close similarity to the permeability curves of iron, as is to be expected. It therefore appears to me that the single-conductor, steel-armored cable is unsafe to use, and should be avoided as far as possible; where it is used, it is not safe merely to make a few measurements and tests of impedance and resistance to determine its probable behavior, but the investigation must be extended over the entire range of operating conditions which the cable may meet under normal as well as abnormal conditions of service. I would rather use two-conductor cable even if unarmored. With single-conductor cables of higher voltages, in addition to the phenomena of losses, and possibly related to them, there appear a number of very high frequency disruptive effects, some of them unexplained, which have in a number of instances of station wiring led to the abandonment of armored cables, and even of lead-covered, single-conductor cables in favor of unarmored cables. I believe, in general, the conclusion is that a single-conductor cable, whether lead sheathed or steel armored, is not safe in electrical systems.

J. B. Whitehead (by letter): Consider a double-conductor submarine armored cable connected for carrying the track and trolley circuits across a drawbridge. The conductor in the track circuit has in parallel with it all possible ground paths between the two sections of track on opposite sides of the draw. The track is usually well grounded at such points, either by the bridge and supports or frequently by intention by means of ground plates in good water bottom. A steel cable or a chain is also often installed as a protection against dragging anchors. The armor and lead cover of the cables also contribute their conductivity. If all these grounded circuits are tied in together it is not difficult to imagine a considerable diminution if not extinction of current in the track conductor of the cable. The cable thus operates more or less completely as a single conductor concentric cable, and it would be difficult to prevent its doing so.

Three single-conductor armored cables 200 ft. long have been in service in the trolley circuit of a 6600-volt, single-phase road for over a year, under widely varied conditions of load and have given no evidence of trouble.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 29, 1909.

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CORONA PHENOMENA IN AIR AND OIL AND THEIR RELATION TO TRANSFORMER DESIGN

BY W. S. MOODY AND G. FACCIOLI

Several experimenters have investigated the phenomena of corona and published very complete results of their investigations, which, however, have been confined almost entirely to the conditions found in transmission lines. The experiments recently made by the authors, some of which will be described in this paper, were not undertaken with any idea to add to the available information applicable to transmission lines, but rather with reference to apparatus, and especially static transformers.

In transmission lines we have the simplest form of condenser to consider in studying the corona effects. In apparatus, the forms of condenser that must be considered are evidently very much more complex, because of the relatively shorter length of the dielectric, the irregular shapes of the condenser surfaces, and the combination of solid, liquid, and gaseous dielectrics.

No attempt will be made to make the paper an exhaustive treatise on the subject; in fact, the experiments have shown so many unexpected results that it would be quite impossible to do so from the experiments so far completed. It is hoped simply to bring out some confirmation of existing knowledge and some distinctly new observations, to point out the very complex nature of the study, and how essential further knowledge will become with the increasing demand for apparatus generating 100,000 volts and over.

The first series of tests were made on apparatus consisting of a cylindrical conductor parallel to a plate. Let us briefly recall the theory giving the distribution of the electric field in a condenser of this type.

The capacity of such a condenser is

$$C = \frac{1}{2 \log_n \dfrac{2\,D}{\rho}} \text{ c.g.s.}$$

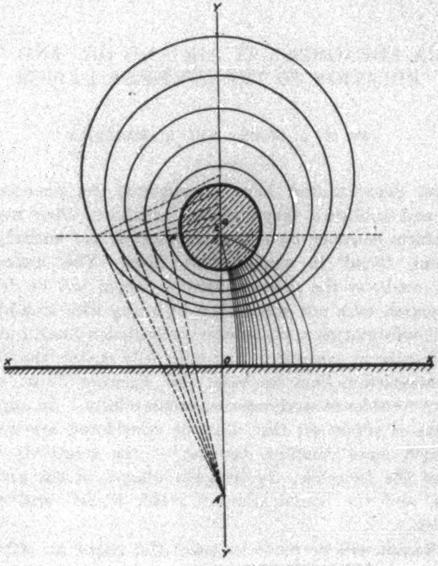

Fig. 1.

electrostatic units per unit length, where ρ is the radius of the conductor and D is the distance between the center of the conductor and the plate. This formula is sufficiently accurate if ρ is small with reference to D.

Fig. 1 represents such a condenser. The plate $x\,x$ is at a distance $C\,O$ from the cylindrical conductor. The diameter of the conductor has been chosen comparatively large in proportion to the distance from the plate in order to have a distinct picture of the equipotential surface, etc. The lines of force are circles with their centers on $x\,x$ and all pass through the points $A\,A'$, such that $O\,A = O\,A'$ and $C\,A = D - \sqrt{D^2 - \rho^2}$

The equipotential surfaces are represented in cross-section by a series of circles perpendicular to the lines of force and with their centers along the axis $Y\,Y$. If we imagine these equipotential surfaces materialized and metallic, we do not change the distribution of the electric field in the condenser. If, therefore, we wish to know the potential existing at a point P, we can imagine that the condenser formed by the conductor and the equipotential surface passing through P, is in series with the condenser formed by this equipotential surface and the plate $x\,x$.

The capacity between the cylindrical surface passing through P, and the plate $x\,x$ is given by

$$c' = \frac{1}{2 \log_n \dfrac{2\,D}{m}}$$

where m is the radius of the equipotential cylindrical surface passing through P, m being supposed to be small with reference to D. The potential at the point P will then be

$$E' = E\,\frac{C}{c'} = \frac{E \log_n \dfrac{2\,D}{m}}{\log_n \dfrac{2\,D}{\rho}}$$

The potential of $x\,x$ is assumed as zero, and E is the potential applied to the cylindrical conductor. This formula is general and gives the potential of any point P in the field, provided m be small with reference to D.

If we want the potential gradient κ at any point P, we must take the first derivative of the potential and we arrive at

$$\kappa = \frac{1}{m}\;\frac{E}{\log_n \dfrac{2\,D}{\rho}}$$

and using the decimal logarithm we have

$$\kappa = \frac{1}{m}\;\frac{0.434\,E}{\log_{10} \dfrac{2\,D}{\rho}}$$

It is very important to know at which point of the field this potential gradient κ is maximum. Obviously κ is maximum for $m = \rho$, and the maximum gradient is therefore

$$\kappa_{max} = \frac{0.434\,E}{\rho \log_{10} \dfrac{2\,D}{\rho}}$$

The potential gradient is then a maximum at the surface of the conductor, and when κ maximum is higher than the resisting power of air, corona will appear on the conductor. From a number of experiments the maximum permissible stress in air at atmospheric pressure seems to be 100,000 volts per inch. The voltage at which corona will appear on a cylindrical conductor is therefore given by

$$E = \frac{100000}{0.434}\,\rho \log_{10} \frac{2\,D}{\rho} = 230000\ \rho\ \log_{10} \frac{2\,D}{\rho}$$

and using the effective value

$$E_{eff.} = 160000\,\rho \log_{10} \frac{2\,D}{\rho}$$

this being true for a sine wave.

Applying this formula to distances $D = 9$ in., 12 in., and 18 in., for diameters of conductors of ⅛ in., ¼ in., ⅜ in., and ½ in., we obtain the following table of voltages necessary to establish corona under different conditions:

D	Diameter of conductor			
	0.125 in.	0.25 in.	0.375 in.	0.50 in.
9 in.	24600	43200	59400	74400
12 in.	25800	45600	63000	79200
18 in.	27600	49200	68400	86400

We must note that this formula does not take into consideration the temperature, barometric pressure and the vapor product; *i.e.*, it is assumed that the constant, 100,000 volts per inch, is regardless of temperature, barometric pressure or vapor product. To check the results of this formula experimentally the apparatus outlined in Fig. 2 was used. A rod 45 in. long is suspended by small bare copper wires $A\,C$ and $B\,D$ from pieces of treated wood hanging from the ceiling. A large iron plate 69 in. long and 27 in. wide, grounded, is brought at a distance D from the rod. The points C and D are connected by bare copper wire; the potential is brought in the wire *M* from the terminal of a transformer whose other terminal is grounded. The volts are read across the secondary of a transformer which is excited by a 60-cycle sine-wave generator. The capacity of the transformer is 100 kw. and by properly grouping the secondary coils, different ratios of transformation are obtainable.

The results given below are the average readings taken repeatedly over a period of two months. The readings taken at different times under the same conditions agree remarkably well. The variations of temperature and barometric pressure were very small, the average temperature being 23 degrees cent., and the average barometric pressure 28.9 in.

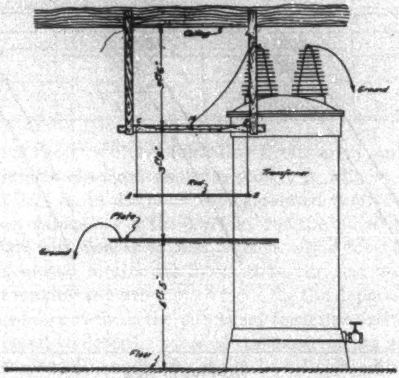

FIG. 2

It must be noted at this point that corona appears on the conductor very abruptly; furthermore, the luminous phenomenon is accompanied by the well-known characteristic noise, so that there is little chance for errors of observation.

The following table gives the voltages at which corona appears on the center of the rod in the apparatus illustrated in Figure 2.

D	Diameter of conductor			
	1.8 in.	0.25 in.	0.375 in.	0.50 in.
9 in.	35600	54500	69800	85000
12 in.	38000	57000	75000	90750
18 in.	41200	61000	80500	95000

The results are plotted in Fig. 3. The curve obtained from the tests is in all cases fairly parallel to the calculated theoretical curve, and the test values may be represented by the formula

$$E = 160000\,\rho \log_{10} \frac{2\,D}{\rho} + f$$

where f is a constant, whose value is 12000 volts. It is not surprising that this relatively small correction should be found necessary when attempting to apply a formula, which has been evolved for transmission lines, to such extreme conditions as existed in these experiments.

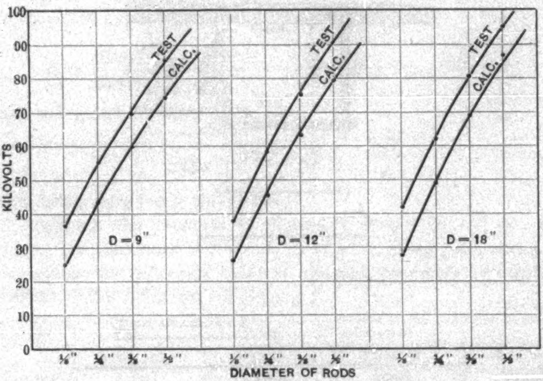

FIG. 3

Professor Ryan has given a formula to determine the conditions necessary for corona between two parallel cylindrical conductors. The maximum value of the voltage at which corona appears, according to this formula is

$$E_{max} = \frac{17.94b}{459.2+t}\,350000\,(\rho+0.07)\log_{10}\frac{s}{\rho}$$

where b is the barometric pressure in inches, t is the temperature in degrees Fahrenheit, ρ is the radius of the conductors and s the distance between conductors.

To apply this formula to our case we must divide E_{max} by 2; we will then have the voltage between one of the conductors and the neutral plane. The correction factor for pressure and temperature is 0.97, and using the effective value of the voltage we finally arrive at

$$E_{eff} = 120000\,(\rho + 0.07)\log_{10}\frac{2\,D}{\rho}$$

This formula is supposed to apply only to conductors $\frac{1}{4}$ in. in diameter and upward. We will, therefore, exclude from the following table the values referring to a rod $\frac{1}{8}$ in. in diameter. The corona voltages, according to Ryan's formula, are then

D	Diameter of conductor		
	0.25 in.	0.375 in.	0.50 in.
9 in.	50500	61200	71500
12 in.	53500	65000	76500
18 in.	57700	70300	83000

Comparing these results obtained by Professor Ryan's formula with the results obtained experimentally, it will be seen that for the rod 0.25-in. in diameter the calculated results are higher than the test values. For the 0.375-in. rod the calculated results are still high, but nearer to test values, while for the 0.50-in. rod the calculated results are lower than the test values.

Without making any attempt to reconcile the departures which have been observed from the published formulas and constants, we will proceed to describe some of the experiments which have shown that so many conditions are to be considered in studying this phenomenon, in connection with apparatus, that it is apparently hopeless to evolve any formula which will be broad enough to be given general application. All the tests were made with a grounded plate as one electrode. It seemed advisable to do this, as it so simplified the problem as compared with the double condenser formed by the plate, conductor and earth, if the plate were ungrounded. The plate used, as before stated, was about 70 in. by 30 in. However, no material variation in results was obtained when a 13-in. disc was substituted for this plate.

In order to obtain consistent results it is, of course, but necessary to know the voltage wave-form which is used in the experiments, as the corona depends on the maximum rather than the average effective voltage as shown by a voltmeter. An attempt was made to determine the voltage by a spark-gap in parallel with the apparatus under test, but the results obtained were very variable, and the attempt was given up for the following reasons:

If the gap was located in the small dark room in which the experiments were performed, the ionization of the air, resulting from the brush discharges, would affect the striking distance considerably.

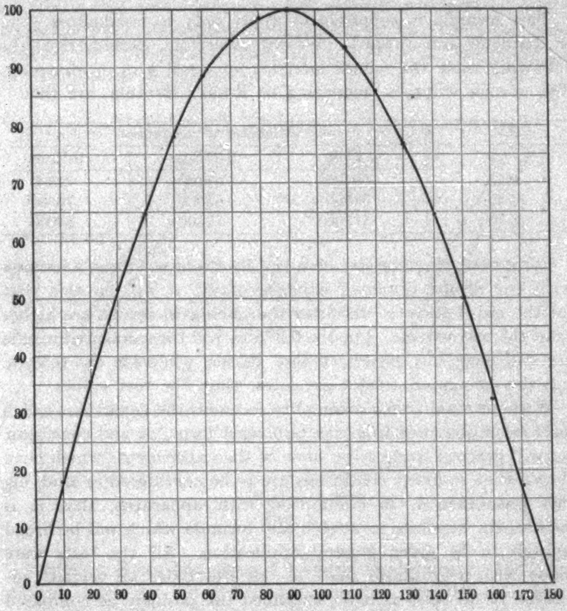

FIG. 4

If the gap was brought outside the dark room, then a source of error was introduced by the long leads required.

There are reasons to suppose that between the gap and the condenser under test some internal oscillations, which upset the results, are set up.

It was therefore thought better to take some oscillograms of electromotive force, reproduced in Figs. 4 and 5, to be sure that the wave-form was the sine wave that it was supposed to be. Fig. 4 represents the electromotive force across the terminals of the high-potential windings of the transformer used in the experiments. It was taken at no load and at 80,000 effective volts, with one terminal of the transformer grounded. The curves show a substantially perfect sine wave.

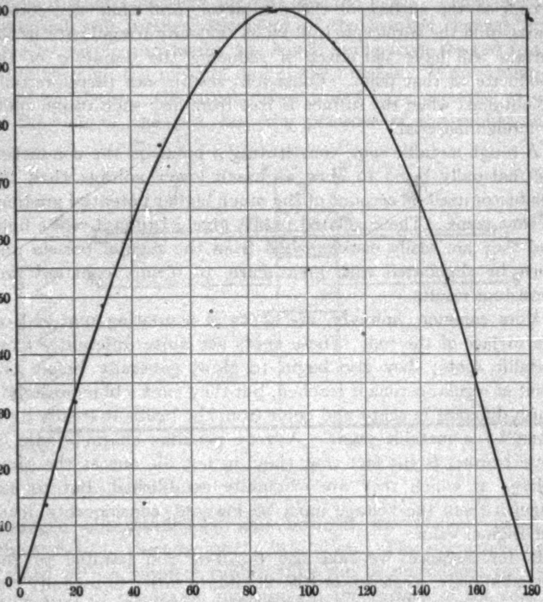

FIG. 5

Fig. 5 gives the shape of the wave of the electromotive force across the high-potential windings of the same transformer, with one terminal grounded at 60,000 volts, when the 0.25-in. rod is connected to the ungrounded terminal and the large iron plate is connected to the grounded terminal, the distance between the plate and the rod being 12 in. The change in the wave form is very small and the effective value is 0.698, the maximum value. It is known, therefore, that the tests were made with substantially sine waves.

Another very important point affecting results was found to be the condition of the surface of the conductor. Assuming, as we know to be the case, that the maximum potential gradient occurs at the surface of the conductor, and that the corona starts from the surface, it is obvious that any irregularity in the surface will have the effect of reducing the diameter of the conductor at that point. Consistent results can therefore only be obtained when the surface is free from any such rough spots or foreign material.

A rough metallic spot, constituting a point on the conductor, will naturally begin to glow at much lower voltage than the conductor itself on account of the much higher potential gradient at that point. These isolated points give a brilliant white light and they are easily distinguished from the regular corona and must be eliminated with great care, to obtain constant and consistent results.

More common, however, are spots of insulating material on the surface of the rod. These spots act quite differently from metallic spots; they also begin to glow, generally before the point of regular corona is reached, but they emit a blue, unsteady brush different in shape and color from the brilliant steady light given by a metallic point. A very peculiar characteristic of these brushes is the fact that they do not die out at the same voltage at which they are originally established, but to extinguish them the voltage must be lowered considerably from the original value.

If, for instance, we take the 0.375-in. rod parallel to the grounded plate, as shown in Fig. 2, and, in order to magnify the phenomenon we slip a piece of rubber tube 3 in. long on the rod and then increase gradually the potential of the rod, we find that at 78,500 volts each edge of the rubber tube gives a blue, silent, unsteady brush, which increases in length and volume with increasing potential. If the voltage is lowered below 78,500 volts, the brushes do not die out until 68,000 volts is reached. To reëstablish the brushes after they have been extinguished 78,500 volts are again necessary.

In order to obtain consistent results, great care was taken during the tests to work with clean, uniform surfaces of conductors, which condition is not easily obtained. But the effect of insulation on the conductor appeared so peculiar that an investigation of this matter was started and very interesting results were gathered.

If in the test just mentioned, we raise the potential above 78,500 volts, the brushes at the edge of the rubber tube increase, as has been said, in length and volume until they span the whole distance between the rod and the plate. Increasing the potential still further, the color of the brushes changes from blue to purple and finally the spark jumps from the rod to the plate through the mass of one of the brushes. If no insulation were on the rod, the break-down would have occurred at one of the ends of the rod, but the presence of the rubber tube changed the conditions and brought the weakest point of the system to the edge of the insulation. This phenomenon obtained with a piece of rubber tube can be reproduced by using any kind of insulating material on the surface of the rod. A thin coat of paraffin on the rod will produce the phenomenon as well as a glass or mica tube, a knot of varnished cambric tape, a rubber cork, a disc of sulphur, or the like.

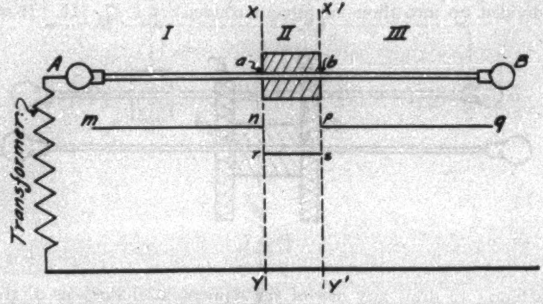

FIG. 6

Referring to Fig. 6, *A B* is a rod 0.25-in. in diameter, ended by two spheres 2 in. in diameter and brought 12 in. away from a plate. If we apply a difference of potential between the rod and plate, the system will break down at one of the spheres at 144,000 volts. If a rubber cork $\frac{3}{4}$ in. in diameter and 1 in. in length is slipped on the center of the rod, the system breaks down at one of the edges of the cork at 141,000 volts. If the cork is removed and replaced by varnished cambric tape wound on the rod, the system breaks down from the edge of the varnished cambric insulation at 135,000 volts. We see, therefore, that not only the edge of the insulation has become the weakest point of the system, but that the value of the breaking-down point has also been decreased. It would be superfluous to state the many tests performed on this point but they all agree and confirm the results already given.

An explanation of these results will be simple, we believe, if the disturbances in the field of electric forces, which take place on the introduction of the insulating material around the center of the rod *A B*, are investigated in the following way: Let us imagine the system of conductors and insulations in Fig. 6 divided up into three contiguous condensers I, II, III. If we attempt to draw any one of the equipotential surfaces of the system, we will see that in the condensers I and III, the sections of the equipotential surface are represented by the lines *m n* and *p q* at the same distance from *A B*. But in the condenser II, which has a material of high specific inductive capacity near the rod, the trace of the equipotential surface will be lower than *m n* and *p q*, say *r s*.

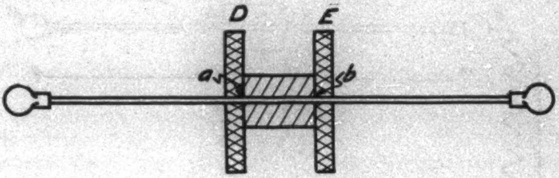

FIG. 7

In the vertical planes *X Y* and *X′ Y′*, the conditions of the field are very peculiar, inasmuch as the voltage of each point along these lines. considered as a part of condenser I, is different from the voltage of the same point considered as a part of condenser II. The result, we believe, therefore, shows the existence of a transverse stress along the lines *X Y* and *X′ Y′*, which causes the appearance of the brushes and the final breakdown.

If this is correct we should be able to stop the formation of brushes in *a b* by equalizing the potential along the planes *n r* and *p s* by metallic surfaces. If we slip on either side of the insulation two metallic discs (Fig. 7) having diameters as large, or larger, than the insulation, we should expect that we would eliminate the brushes *a b*. Tests show this to be the result. Two tinfoil discs 2 in. in diameter were put on the rod, as shown in Fig. 7. The edges of the insulation were entirely free from brush discharge and the condenser broke down at one of the spheres at 144,000 volts.

It is to be noted that although the metallic discs were nearer to the plate than the ends of the rod still these ends remained the weakest point of the apparatus. But we would expect even more from the metallic discs. If we apply the same methods of reasoning used before, and we picture to ourselves the equipotential surfaces of the condenser, we would expect that the introduction of these discs on the rod would have the effect of relieving the stress from a certain length of the rod on each side of the discs. The test proves that this assumption is correct.

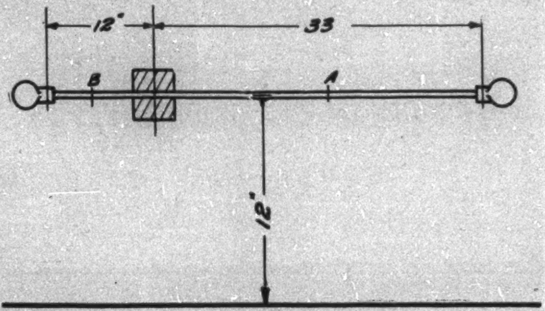

Fig. 8

We have seen that a rod, 0.25-in. in diameter and 45 in. long, parallel to a grounded plate, and 12 in. away from it, begins to glow at 57,000 volts. If we wrap tin-foil in the center of the rod, making a little cylinder 3 in. long and 1 in. in diameter, corona will appear in the middle of the two sections of the rod at 62,300 volts. Let us shift our tin-foil cylinder on the rod so that the two sections will be of different length. Then, as shown in Fig. 8, the middle of the longer section *A* glows at 59,250 volts, while the middle of the shorter section *B* does not glow until 76,500 volts is reached.

If we put on the same rod two cylinders of tin foil, spaced as shown in Fig. 9 the center of the middle section *B* glows at 69,750 volts, while the centers of the other two sections *A* and *C* glow simultaneously at 75,750 volts. This test shows conclusively that the metallic cylinders cast, so to speak, a shadow on the conductor on each side, protecting a certain length of it, and increasing, if properly spaced, the effective diameter of the rod.

Figs. 10, 11, 12 will serve as a summary of what we have seen regarding the influence of the condition of the surface of the conductors. Fig. 10 shows a 0.25-in. rod 88 in. long having a regularly distributed corona against the ground plate 12 in. from it. The photograph was taken at 85,000 volts. Fig. 11 shows the same rod in exactly the same conditions as before, at the same voltage, but a piece of varnished cambric tape is wrapped on the center of the rod and a strong brush is produced at this point. In Fig. 12 we have the same rod as before at the same voltage but with three tinfoil discs 2 in. in diameter equally spaced on the rod. The corona is very small and limited and very different from the one shown in Fig. 10.

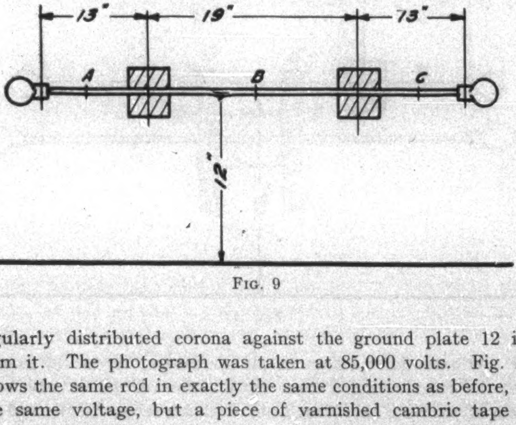

Fig. 9

A very interesting point was brought out in further study of the results obtained with the combinations shown in Figs. 8 and 9. When the voltages at which corona appeared on different portions of this apparatus are tabulated with reference to the free length of the conductor *A B* we find the following:

Free length of rod	Glowing point
45 in.	57,000 volts
31.5 in.	59,250 "
21 in.	62,300 "
16 in.	69,750 "
11.5 in.	75,750 "
10.5 in.	76,500 "

This shows that it takes an increasing voltage to establish corona the shorter the length of the rod. In other words, corona is not a fixed quantity for a given voltage and diameter of rod, unless the length of the rod is great and the diameter uniform. In order thoroughly to demonstrate this point, three rods ¼ in. in diameter were experimented with. The rods were of different length, all the other conditions of the test being identical. The arrangement was the one represented in Fig. 2 and the distance between the rod and the grounded plate was 12 in. The results of the test are as follows:

FIG. 10

Length of rod	Corona voltage
45 in.	57000 volts
23 in.	68000 "
12 in.	83500 "

These results are plotted in Fig. 13.

We see immediately that the values of this table differ from the corresponding values of the preceding table. We must realize, however, that the conditions of the test are somewhat different in the two cases and that the " suspension " of the rod might influence the results.

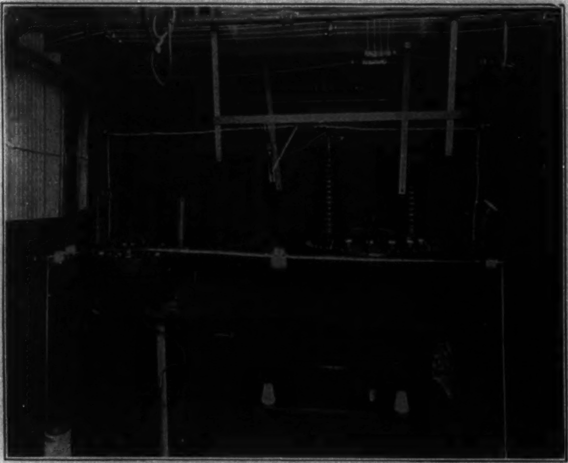

FIG. 11

Let us return to our apparatus as represented in Fig. 2, where the rod is suspended by copper wires and the suspension wires are connected together by the wire *C D*. Let us observe accurately what happens when we gradually raise the potential of the rod, which is 45 in. long, 0.25-in. in diameter and 12 in. away from the grounded plate.

At 57,000 volts the rod was dark.

At 58,000 volts the center of the rod glowed.

Theoretically we would expect that as soon as the critical voltage is reached corona would appear over the whole length of the rod. This is because we assume that the intensity of the field is constant all along the rod and the equipotential surfaces in the immediate neighborhood of the rod are cylinders practically concentric with it. This test shows, however, that the intensity of the field is not uniform throughout the length of the rod.

If we measure the exact location and length of corona at different voltages, and note its spreading with increasing potential, we will have an idea of the distribution of the field in the different parts of the rod. At 58,000 volts the length of the glowing portion of the rod is 15 in., exactly in the center. At 80,000 volts its length becomes 33.5 in.; that is, the whole rod glows, except 6 in. near the suspension points. The system breaks down at 113,000 volts from one end of the rod, although even at this voltage the portion of the rod near the suspension wires remains dark.

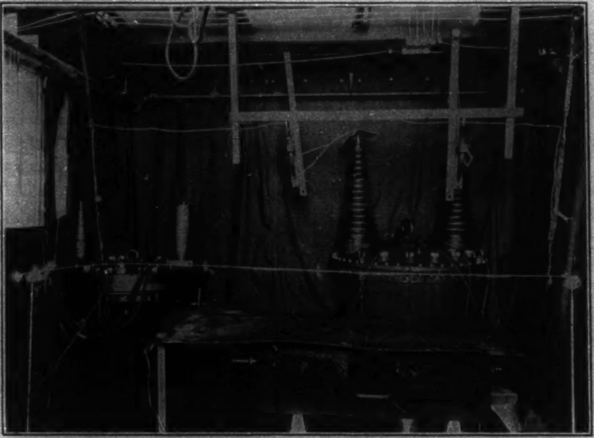

Fig. 12

Now let us repeat this test, but let us modify the suspension slightly. We eliminate the bridging wire *C D* and bring the high potential lead to *C*. The suspension wire *B D* is, therefore, connected to the rod only.

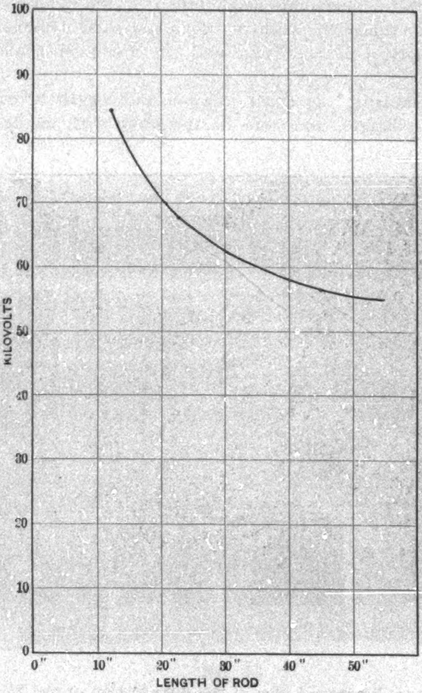

FIG. 13

At 54,000 volts the rod was dark.
At 55,000 " corona was 15 in. long in the center.
At 60,000 " " " 22 " "
At 80,000 " " " 33 " "
At 100,000 " " " 35 " "

At 112,000 volts the system broke down from one of the ends to the plate.

We have changed the value of the voltage at which corona starts, although we have not changed practically the spreading of corona at high voltage. Finally let us remove the copper wire *B D* and replace it by silk tape. In this case the results are as follows:

At 50,000 volts the rod was dark.

At 51,000 volts, the portion of the rod near *B*, or near the silk tape suspension, glowed for the length of 21 in. measured from *B*; in other words, the rod was divided into two sections, of which 24 in. near *A* were dark and 21 in. near *B* glowed. Increasing the voltage, the corona approached more and more to the point *A*.

At 60,000 volts the corona was 33 in. long.

At 80,000 volts the corona was 40 in. long, or 5 in. near *A* remained dark.

At 90,000 volts the corona was 41 in. long, or 4 in. near *A* were dark.

At 105,000 volts the corona was again 41 in. long and at 112,000 volts a spark jumped from *A* to the plate.

The phenomenon is so delicate that it actually makes a difference whether the silk ribbon is tied in a knot around the rod or whether the rod is placed in a loop made by the ribbon. The knot gives a brush, while the loop originates a silent glowing on the rod near *B* before corona starts. The results obtained with the insulating suspension are not, generally speaking, so certain and constant as those obtained with the suspension represented in Fig. 2. This is the reason why the latter suspension has been chosen to perform comparative tests.

We must note that in all these experiments the " ends " of the rod do not affect the character of the phenomena. In fact similar results are obtained whether the rods are ended by spheres of large diameter or not. The curves in Fig. 14 represent the voltages and the corresponding lengths of corona in the three cases mentioned above. Curve 1 refers to the suspension shown in Fig. 2. Curve 2 refers to the same suspension without the bridging wire *C D*. Curve 3 refers to the silk-tape suspension.

A doubt may arise in connection with the results of these experiments, as one might suppose that the dimensions and the position of the grounded plate might affect the location and spreading of corona. This, however, is not the case. If the grounded plate is removed and the rod is left in the same place, forming a condenser with the floor, ceiling, walls, etc., of the room, the same results are obtained.

The voltage at which corona starts is naturally different, but the general appearance of the phenomenon is the same as before. If both ends of the rod are suspended by copper wires the center of the rod will glow first and the parts in the immediate neighborhood of the suspension points will not glow at the highest voltage. If one end of the rod is suspended by insulating material, this end will glow first and the corona gradually approach the excited end.

In conclusion, we have seen that the corona voltage is affected by many conditions which can hardly be taken care of in a formula. We have shown the influence of the following:

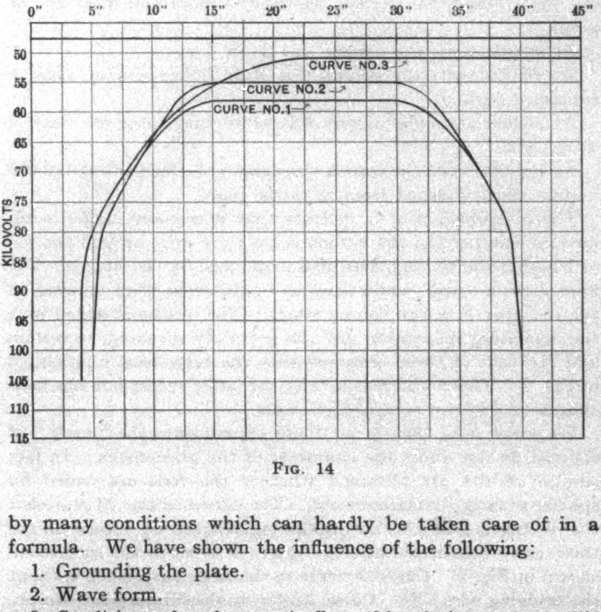

FIG. 14

1. Grounding the plate.
2. Wave form.
3. Conditions of surface, and effect of insulating and metallic discs.
4. Length of rod.
5. Suspension and consequent localizations and spreading of corona.

Before we leave this apparatus—a cylindrical conductor parallel to a plate—we might attempt to check, in a general way, the theoretical law which gives the corona voltage as a function of the diameter of the rod and its distance from the plate. If we take a rod of radius ρ' at a distance D' from the plate, and another rod of radius ρ'' at a distance D'' from the plate, the two rods ought to glow at the same voltage, if

$$\rho' \frac{\log 2\,D'}{\rho'} = \rho'' \frac{\log 2\,D''}{\rho''}$$

Unfortunately the change in the distance required by a small change in diameter is very large. For instance, if we take two rods, one 0.25 in. in diameter, and the other 0.375 in. in diameter, the distances for the same corona voltages are respectively 9 in. and 28 in. Similarly, if we compare a ⅜-in. rod and a 0.25 in. rod, the theoretical distances are respectively 6 in. and 31½ in.

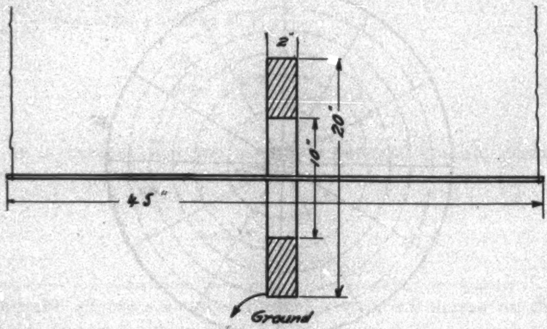

FIG. 15

For the reasons given in the foregoing, the tests to check this law proved to be erratic, as might be expected, but in general the tests show that a small rod at a comparatively great distance from the plate requires a higher voltage than a large rod at a correspondingly small distance from the plate. However, on account of the great difference in distances, it is almost impossible to reproduce exactly the same conditions of test in both cases, and, from what we have seen, the behavior of the electric field is so sensitive that we would not be surprised at the apparent inconsistency between theory and test.

The second type of condenser on which experiments were performed is illustrated in Fig. 15. Different rods 45 in. long, suspended at both ends by copper wires, were located in the center of a metallic disc. The dimensions of the ring are 10 in. inside diameter, 20 in. outside diameter and 2 in. long. The disc and the portion of the rod covered by it constitute a condenser whose theory we will briefly recall.

Fig. 16 represents a condenser of this type, C being the inside conductor of radius ρ'', G being the outside cylinder of radius ρ'. The lines of force of such a condenser are along the radii, and the cross-sections of the equipotential surfaces are circumferences concentric with the plates. If we wish to find the potential of a point P at a distance m from the center we can imagine the equipotential surface passing through P materialized and metallic, as we did before.

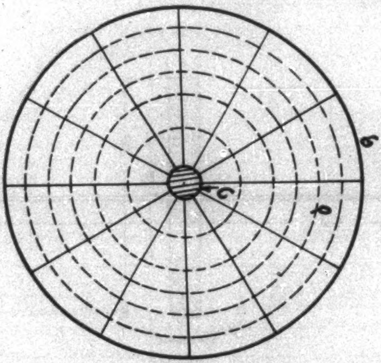

FIG. 16

Now the condenser made by the conductor C and the cylinder G is equivalent to two condensers in series, one from the conductor C to the equipotential surface P, the other from this surface to the cylinder G. If we call C the capacity between the conductor C and the cylinder G, C' the capacity between the equipotential surface P and the cylinder G, zero the potential of G, E the potential of C, E' the potential of P, we have

$$E' = \frac{C}{C'} E$$

$$\text{But } C = \frac{1}{2 \log \frac{\rho'}{\rho}} \text{ per unit length}$$

$$C' = \frac{1}{2 \log_n \frac{\rho'}{m}} \text{ per unit length}$$

Therefore:

$$E' = \frac{\log_n \frac{\rho'}{m}}{\log_n \frac{\rho'}{\rho}}$$

The potential gradient at P is

$$\frac{dE}{dm} = \kappa = \frac{0.434\, E}{m \log_{10} \frac{\rho'}{m}}$$

It is evident that the maximum potential gradient occurs when $m = \rho$, and is given by

$$\kappa_{max} = \frac{.434\, E}{\rho \log_{10} \frac{\rho'}{\rho}}$$

and the effective voltage at which corona will appear on the inside conductor is, in volts

$$E_{eff} = 160000\, \rho \log_{10} \frac{\rho'}{\rho}$$

If we apply this formula to the case of Fig. 15 for $\rho' = 5$ in. and for diameters of rods $\frac{1}{8}$ in., $\frac{1}{4}$ in., $\frac{3}{8}$ in., $\frac{1}{2}$ in., we have

Radius of conductor	Corona voltage
0.0625 in.	19000
0.125 in.	32000
0.187 in.	42600
0.250 in.	52000

In attempting to check these calculations with the apparatus shown in Fig. 15, the metallic cylinder was grounded and the rod connected to one of the terminals of the testing transformer, whose other terminal was grounded. The rod was 45 in. long and the cylinder 2 in. long, the latter being located in the center of the rod. The following results were obtained:

Radius of conductor	Corona voltage
0.0625 in.	26500
0.125 in.	40500
0.187 in.	52000
0.250 in.	62000

The tested values are again higher than the calculated values, but their difference is not constant. The discrepancies between tests and theories are undoubtedly explained by the fact that the formula applies to cylinders of indefinite length, whereas one cylinder in this case was very short and consequently the disturbing influences of the ends of the cylinder were proportionately very great.

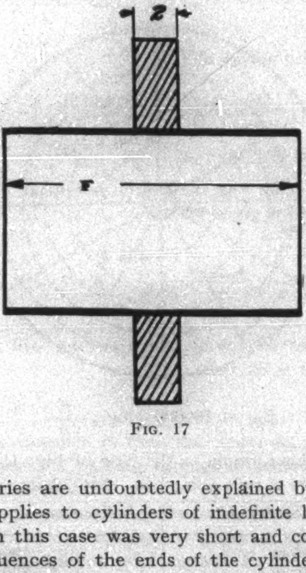

FIG. 17

Just how the length of the outside ring influences the results can be easily seen from the further tests made with apparatus as shown in Fig. 17. Metallic tubes of different lengths were inserted and supported by the cylinder previously used, and the following results were obtained with different lengths *F*:

Radius of rod	2 in. long	6 in. long	18 in. long
0.0625 in.	26500	25200	24000
0.125 in.	40500	38500	36500
0.187 in.	52000	48500	47500
0.250 in.	62000	——	54500

The longer the cylinder the lower is the corona voltage, which shows a more uniformly distributed field in the center of the apparatus; that is, the longer the cylinder the nearer we approach the theoretical results.

On the other hand, with the arrangement shown in Fig. 15, if the length of the rod is decreased, the voltage at which corona appears is increased, as shown by the following table:

Length of rod	Corona voltage
45 in.	40500
23 in.	41500
12 in.	44000

We obtain identical results if instead of using shorter rods, we shift the suspension wires nearer together so that the free lengths of the rod between the suspension points are respectively 45 in., 24 in., and 12 in. We see here again, as in the other type of condenser, the protecting influence of the suspension wires, which relieve the stress for a considerable length on the surface of the rod.

We would expect also to find that the cross-section of the ring has a pronounced influence on the results. If we take a pipe 1 in. in diameter, bend it in a ring 10 in. in diameter, pass through its center rods 45 in. long and of varying diameters, we then obtain the following results:

Radius of rod	Corona voltage
0.0625 in.	29600
0.125 in.	45000
0.187 in.	58000

The corona voltage has been increased considerably. It should be borne in mind, however, that we have not only changed the cross-section of the ring, but we have also decreased its length, the pipe used being only 1 in. in diameter.

The results of all these tests show that conditions existing in the field between the ring and the rod are very different from those assumed in our theory. The lines of force have commonly been thought of as perpendicular to the surfaces of the outside cylinder and uniformly distributed along its length. Evidently this cannot be the case when the length of the cylinder is short. The density of the field is a maximum in the central part of the rod and decreases in intensity towards the ends. This can be clearly shown by observing the fact that when the rod is excited from both ends the middle begins to glow at very much lower voltage than is required to distribute this glow upon the entire length of the rod. In fact, with the proper combination of apparatus, the voltage applied can be quite accurately determined by the length of the rod that glows. The following results were obtained by again using a 0.25-in. rod in the apparatus shown in Fig. 15.

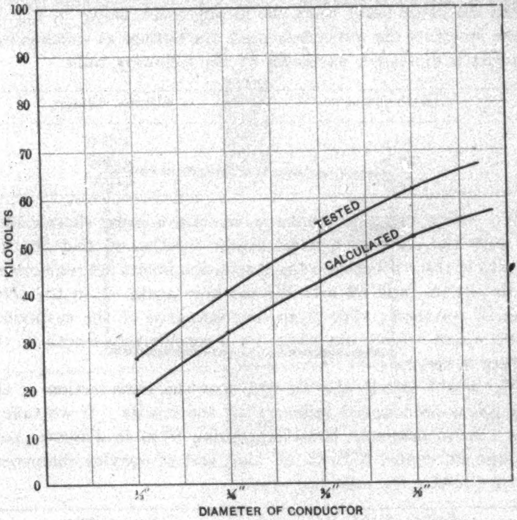

Fig. 18

At 40,000 volts the rod was dark.

At 40,500 the corona appeared in the center under the ring but the glowing portion was shorter than 2 in., which is the length of the outside cylinder.

At 45,000 volts the corona was 7 in. long in the center of the rod; protruding 2.8 in. on each side of the ring.

At 50,000 volts corona was 10 in. long
At 55,000 " " " 15 in. "
At 60,000 " " " 16 in. "
At 65,000 " " " 23 in. "
At 70,000 " " " 26 in. "

At 75,000 volts the apparatus broke down from the rod to the ring. Then at 40,500 volts the intensity of the field was not uniform under the cylinder, but was a maximum in the exact center of the rod. At 45,000 volts the critical value was reached over a portion of the rod much longer than the cylinder itself.

If we observe the glowing part of the rod at 70,000 volts, we will notice that its apparent diameter is constant for about 11 in. in the center, then it decreases gradually toward each end. But at comparatively large distances from the ring and at high potential, the surrounding bodies may have considerable disturbing influence on the glowing of the rod. If we change our suspension, using some insulating material at one end, or if we modify the conditions of the ends of the rod by using spheres of large diameter, the results are not affected, and the potential at which corona appears and the positions of corona on the conductor are unaltered.

On the other hand, the effect of insulation and metallic sleeves on the conductor is the same as in the case of a rod against a plate. If we tie a piece of varnished cambric tape in the center of the 0.25-in. rod shown in Fig. 14, brushes will appear at the edges of the knot at 30,700 volts and the apparatus will break down at 40,500 volts from the insulation to the ring.

If we shift the knot of insulating tape to a distance of 3 in. from the edge of the ring, corona will appear on the conductor under the disc at the usual voltage—40,500 volts. But at 33,000 volts a brush has appeared at the edge of the insulating material facing the ring. Increasing the potential, the brush increases in strength, and at 45,000 volts a spark jumps from the insulation to the ring.

Let us shift the insulation knot 6 in. away from the edges of the ring. A brush will appear simultaneously with corona at 40,500 volts, and at 64,000 volts the system will break down again from the insulation to the ring. If we shift the varnished cambric tape still further away from the ring, say 12 in., the brush starts at 41,000 volts, but, in this case, the apparatus breaks down from the center of the rod to the ring at 75,000 volts. This is the voltage at which the system would have broken down if we had had no insulation on the rod.

It was necessary to remove the knot of varnished cambric 12 in. away from the ring to counteract the effect of insulation on the surface of the conductor. The breaking-down point was lowered considerably by the presence of the varnished cambric, and the remarkable short-circuiting effect of the brush caused the spark to strike through a much longer distance than the shortest path between the two plates of the condenser.

Metallic sleeves, we have seen, have the opposite effect. If two brass sleeves 0.5 in. outside diameter and 1 in. long are placed on the rod near its suspension points, the center point of the rod glows at 40,500 volts. If we shift the two brass cylinders nearer together so that each one is 12 in. away from the ring, the rod will glow again at 40,500 volts. If we bring the brass cylinders 3 in. away from the edge of the ring, corona will appear in the center of the rod at 41,500 volts. When the brass cylinders are placed 1 in. away from the edges of the ring the center of the rod begins to glow at 47,500 volts. If we bring the two brass cylinders still nearer, so that they are 2 in. apart, corona will appear only at 50,000 volts. The presence of the two metallic sleeves, therefore, does increase the apparent diameter of the rod, as far as corona is concerned, for a considerable distance on either side of the disc. In the last test the corona voltage was 50,000 instead of 40,500, which is equivalent to increasing the diameter of the rod from 0.25 in. to 0.375 in.

From all these experiments we can draw the general conclusion that the voltage at which corona appears in apparatus of limited dimensions, not only depends on the dimensions of the apparatus itself and the mutual action of the different parts, but is also a complex function of several quantities and conditions. Therefore, the formula which takes into consideration only the principal dimensions of the condenser between which the electric stress exists could not give correct results.

Before closing, we wish to say a few words with reference to corona as it exists under oil. We have often heard it said that the use of oil eliminates corona, but such is not the case in our opinion. There are some distinct differences in the manifestation of corona in air and in oil, but, so far as our present rather limited experimentation goes, we believe there is no essential difference in this manifestation in the two substances.

If we submerge two needles 12 in. apart in oil, and raise the difference of potential between them, there is no noticeable glow given off up to 100,000 volts, but with 1000 volts more, the glowing is very perceptible in the shape of a small steady brush, noiseless and green in color. We have here, then, not only a corona, but the same characteristic that is found in air corona; namely, that a very slight difference exists between the voltage at which there is no corona and that at which it appears.

If we raise the potential still further, the brushes increase in size and eventually touch each other and soon after cause a disruption of the oil. If the needles, instead of being 12 in. apart, are only 6 in. apart, the corona will be established at about 78,000 volts; if the needles are 3 in. apart, the corona will start at about 72,000 volts.

If before breakdown takes place, we decrease the difference of potential between the needles, the corona will disappear at the same voltage at which it started. Furthermore, the oil that is in the gap is set in violent motion, which is maintained so long as a stress exists. Analogous results can be obtained by using the needle opposed to the plate; that is, at a certain voltage the point will emit a steady luminous brush, which is similar to the brushes obtained in air.

Experiments were made on a condenser consisting of a cylindrical conductor and a plate under oil, as follows: A wire 0.02 in. in diameter and 15 in. long was stretched between two brass supports and a plate was placed 6.5 in. from the wire and parallel to it. One terminal of the transformer was connected to the wire and the other to the plate, and all were submerged in oil. At 49,000 volts everything was dark, at 50,000 volts the small wire glowed; when the potential was raised, the glow became more and more pronounced. The thickness of the corona appeared to be considerably more than in air and was more unsteady.

If, instead of 0.02 in. wire, we use 0.04 in. wire, the corona will not appear until 60,000 volts. In this case, the corona is made up of a large number of contiguous and unsteady brushes which cover the whole length of the wire. Using a wire 0.05 in. in diameter under the same condition, corona does not appear until 80,000 volts. In this case we obtain no regular glow, but very unsteady distinct brushes that shift their position along the wire. If we use 0.125-in. wire, the brush will appear at about 100,000 volts, and if we raise the potential, the brush will appear and disappear again irregularly; that is, we have an intermittent luminous phenomenon, which represents more of an interrupted arc then the regular corona. In explanation of this phenomenon, we would suggest that the very violent movement of oil under such dielectric strains may account for the unsteady nature of the corona at these higher potentials. It would seem, therefore, that the larger the diameter of the wire, and, consequently, the higher the voltage required for corona, the more the phenomenon under oil differs from the phenomenon in air.

With our present knowledge, the comparison of values between corona voltage in air and under oil is very difficult and unsatisfactory. Under oil it is only with wires of small diameter that the corona voltage is sufficiently abrupt and constant to be measured consistently, while in air it is the small wires with which it is difficult to get consistent results. Such small wires in air depart markedly from the law that expresses the corona phenomenon on larger wires. The larger wires under oil, as we have said, give very unsteady and therefore, unsatisfactory results.

Similar tests were tried with wires located in the center of a 10-in. cylinder under oil, but the same conditions were met with. With wires above 0.125 in. in diameter, the point at which the corona started under oil was very uncertain and the luminous phenomenon was intermittent or irregular. Distances between wires and plates up to 4 ft. and potentials up to 400,000 volts were used, but the appearance of the phenomenon was always irregular.

Conclusions. We have selected in the foregoing, only a few of the interesting experiments in an incomplete investigation. We trust however that they will be sufficient to stimulate other investigators in this largely unexplored field.

Commercial transformers are now being extensively built to use for voltages where these complex laws of the corona must be generally, if not exactly, known, if their design is to be correctly worked out.

Of course it has been generally appreciated for some years that corona discharges must be avoided, even more in transformers than on the transmission line to which they are connected. When in transformer design only the simple law of the diameter of the conductor and the corresponding corona voltage are considered, and the effects of such factors as the length of the conductor, changes in its diameter and the solid insulation necessary on parts of the conductor are neglected, then these experiments show that it is not surprising that designs apparently similar, have given very different results in service.

DISCUSSION ON "CORONA PHENOMENA IN AIR AND OIL AND THEIR RELATION TO TRANSFORMER DESIGN."

FRONTENAC, N. Y., JUNE 29, 1909

John B. Whitehead: I wish to say a word about the sentence which reads as follows:

> From a number of experiments the maximum permissible stress in air at atmospheric pressure seems to be 100,000 volts per inch.

Dr. Steinmetz has sometimes placed this figure as high as 120,000 volts. Mr. Berg used 100,000 volts in one of his Institute papers; also in his book "Electrical Energy", in which he included a table giving the calculated values at which transmission lines may be expected to discharge between wires. There is a wide discrepancy between the calculated values given by Berg and those observed by Mershon, in fact Mershon's values are 30 per cent lower than those calculated by Berg. I have figured this discrepancy for two cases. Berg gives a figure of 104,000 volts approximately for one of the cases investigated by Mershon, whereas Mershon's value lies between 62,000 and 74,000 volts, according to the vapor product. In another case Mershon gives 42,000 and Berg 60,000 volts. Mr. Moody finds that the values he observed are even higher than the calculated values using 100,000 volts as the intensity at which air may be expected to break down. He is, therefore, further than Berg from Mershon's values. All of these conclusions are on the assumption that Mershon's critical point is the point at which the corona becomes visible. I understand this is true, although I should like to have it confirmed. At any rate, we now have quite a discrepancy, about 50 per cent, in values of voltage at which discharge takes place.

In beginning some work on this subject, I have recently had occasion to calculate the potential gradient necessary to start corona discharge, with various assumptions as to the nature of the phenomenon. J. J. Thomson has developed a theory of spark discharge. The experimental results have shown that one cannot get a spark in air at any pressure at a lower value than about 350 volts, and moreover at atmospheric pressure 0.01 of a millimeter is the shortest gap for this voltage. There is a constant minimum spark potential and a minimum spark length dependent on the pressure. Applying Thomson's theory to the case of transmission lines, we find it will not serve, for the value at which the air in the vicinity of the wire may be expected to break down, according to this theory, works out to be about 500,000 volts per centimeter.

Taking another theory as to the nature of the phenomenon; Hobbs has shown that corpuscles or elementary negative charges may be drawn from the material of the wire at a potential gradient corresponding to 100 volts acting over 10^{-4} cm. Applying this to the potential gradient in the vicinity of the wire, which is calculable, we again find a value of different order of magnitude from that observed; namely, about 800,000 volts.

Townsend has shown that ionization by collision, which causes conductivity, will take place at lower values of potential gradient even than that necessary to start and maintain a discharge; and if we take his results, and those of Von Schweidler, we find 30,000 volts per centimeter indicated as the potential gradient at which the intensity is sufficient to start secondary ionization. As 30,000 volts per centimeter is about 75,000 volts per inch, I submit that the formulas and observations would be brought into better accord if 75,000 volts per inch were taken as the potential gradient at which air may be expected to break down in the neighborhood of conductors; and further that secondary ionization is the immediate cause of the breakdown.

One of the most interesting things in Mr. Moody's paper is the clearness with which he shows how sensitive the whole phenomenon of corona discharge is, how easily it is affected by the surrounding conductors, and the presence of metal or dielectrics in the field. The immediate effect upon corona of the manner in which the lead wires are brought in is most important. Mr. Moody suggests that perhaps his observed values differ from the calculated values because of the surrounding and shortness of his wire, and the proximity of neighboring conductors. I think this is also the probable explanation of the wide difference between his values and those of Mershon and others.

J. C. Lincoln: I ask Mr. Moody if he made any measurements at all of the energy required by the wire when it is in the condition of corona discharge? There is, doubtless, energy dissipated from the wire when the discharge is taking place. I also ask if any energy is dissipated by the wire at the potential just below the point at which the corona appears? The next paper to be presented speaks of one case where there is a difference of 1000 volts between the point where darkness is obtained and where the corona appears. Is any energy dissipated from the wire at the lower voltage? or is the difference between the disspiation of energy and the non-dissipation of energy as closely related as the appearance and disappearance of the corona?

Ralph D. Mershon: Dr. Whitehead and Mr. Lincoln have both raised a very interesting point which is touched upon by some information Mr. Faccioli sent me a few days ago. It is the question as to the relation between the critical point and the point at which corona discharge begins. Professor Ryan, I believe, came to the conclusion that they were identical. In my work I had no means of determining whether or not they were identical, because my investigation work was done on overhead lines in a place always more or less illuminated, arc lights some distance away, and the illumination was much too great to determine any corona effect. It would not have been practicable to get indoors a sufficient length of line to measure the loss by the method of measurement I employed.

I have pretty nearly come to the conclusion that the two are not identical, that there has to be a considerable amount of loss before there is any visible manifestation. It would seem reasonable to assume that is the case; that an instrument would probably detect the critical point before the eye would. I feel quite sure that the critical point is affected by the conditions of moisture in the atmosphere, and the results I have obtained seem to show that there is a definite relation between that point and what I call the vapor product. On the other hand, Mr. Moody and Mr. Faccioli kindly endeavored, at my request, to find a relation between vapor product and corona, and were unable to find such relation. I was surprised that this should be the case, but after thinking it over have hit upon a possible explanation as to why there should be no relation between corona and variations of such atmospheric moisture as would ordinarily obtain. If the corona effect is a phenomenon of the air itself, which we assume it is, it is conceivable that the addition of moisture to the air would, up to a certain point, play a part comparable to that of a resistance in shunt to an arc. So long as the resistance is at a high value one will not be able to observe, usually, any difference in the behavior of the arc, but if the value of the resistance is progressively decreased the time will come when there would be an appreciable effect. Now, if the amount of moisture in the atmosphere is low enough, it seems to me it will not affect the corona at all, whereas if the atmosphere is heavily enough laden with moisture the corona may be affected.

I think the apparent discrepancy between my results and those of Professor Ryan and the authors of this paper is due to the fact that the critical point as we have been defining it is not coincident with the point at which corona is visible.

S. B. Charters, Jr.: Following out Mr. Moody's suggestion, or probably preceding his ideas, Professor Ryan has already built at Stanford University what he calls a corona voltmeter, which is used to indicate pressure by corona formation. It has a tapered brass rod inserted in a wire cylinder of uniform diameter and produces fairly reliable results. We have observed that it makes a difference in what manner the leading-in wires are attached. The instrument can be thrown out of calibration by bringing the leading-in wire at some other point than the one at which the calibration has been made. Our results in general are in agreement with Mr. Mershon's. The greatest use for this instrument has been in observing transient phenomena, because the corona will follow all sorts of variable phenomena such as the surging introduced by switching. This spring we incidentally checked, in a very small way, the results obtained by the addition of insulators to conductors; while we did not attempt to make any experiments, our results were in accordance with the results here obtained.

We tried a few experiments on corona under oil, getting results which agreed with the above. I wish to emphasize the point of the tremendous mechanical strains to which the oil and wire are subjected under these conditions. We used a No. 34 wire inside a 4-in. cylinder; and the vibration of the wire was sufficient, when under strain, to shake, not only the stands, but to move a weight of several pounds of iron. We moved the whole stand and iron bodily, simply by the vibration of the small wire under the static strains.

W. S. Moody: I think the only answer needed is to the question which Mr. Lincoln asked; that is, whether we attempted to determine the energy used in creating the corona, and whether we could distinguish between the power required to produce a visible corona and the power required for invisible corona, if such exist.

I tried to make it plain that we did not attempt to make any measurements of the power required to produce corona, for the reason that it was impracticable to erect within a dark room of any practical size sufficient highly insulated wire to get a loss from corona of such an amount as would be measureable with any ordinary wattmeter.

Harris J. Ryan (by letter): Through the facts brought out in this paper, the papers and contributions of Mershon, Watson, and others, we are now prepared to understand the practical significance of the conducting character of the normal atmosphere as determined and expressed by J. J. Thomson and other able physicists. They have found that the normal atmosphere contained in a closed vessel conducts a little even under the smallest electric intensities; *i.e.*, kilovolts per inch; that such conductivity is due to the total number of free ions mixed with the volume of air employed; that the origin of the free ions is due to some external ionizing emanations from the walls of the atmosphere container and the conductors employed or from the outer terrestial solar or cosmic sources now known to be numerous; that the value of the current which the atmosphere will thus conduct increases, first regularly with the increase from zero of the electric intensity, then less in proportion until saturation is reached, when the current no longer increases as the electric intensity increases until a critical value is attained: whereas, if exceeded, the atomic structure of the atmosphere is broken, ionization extends from the electrodes and the current is increased at a greatly accelerating rate as the electric intensity is further increased, resulting in the formation of strong coronas or arcs dependent upon circumstances.

For the present purpose we may call the current which is due to the free ions mixed with the atmosphere the *free ion-loss current*, naming *corona-loss current*, that which is due to active ionization. The value of the free ion-loss current depends upon the total number of ions present in the volume of atmosphere employed. When the container is large the free ion-loss current will be large; again when the source of free ions is prolific, the free ion-loss current will be correspondingly great. It is reasonable to expect that with actual line conditions out of doors, because of the vastly greater atmospheric volumes and numerous sources of free ions, especially in great industrial regions, the free ion-loss current would occur in far greater proportions, totally changing its characteristic relation to the initial corona loss current. At Ithaca in 1903-4, by the methods and under the indoor atmospheric conditions there employed, it seemed conclusive that the atmosphere losses are neglibibly small for clean conductors at pressures under the visible corona-forming values.

The earlier results of Mershon in the Rocky Mountains, of Harold B. Smith at Worcester, the results obtained at Ithaca, and the recent continuous current results obtained by Watson at Manchester, England, are in fair agreement as to this point. The more recent results obtained by Mershon at Niagara Falls are not in accord in this respect, and this may be due to the out-of-door character of that region. That is to say, the coincidence or non-coincidence of the electric intensities at which critical loss and visible corona occur may depend considerably upon local conditions; or, to put it another way, when conditions are such as to cause the free ion-loss current to be relatively large, the critical value of the loss current may possibly occur at a decidedly lower pressure than that which will start the visible corona.

As to the volts per inch at which the normal atmosphere is ruptured: J. J. Thomson is likewise authority for the value of 30,000 per centimetre at which active ionization occurs; this corresponds to 76,200 volts per inch. In the work at Cornell alternating pressures that start coronas on conductors having diameters ranging from 0.05 in. to 0.65 in. were found to produce an electric intensity in the atmosphere next to the conductor surface ranging from 190,000 volts per inch for clean conductors with diameters at 0.05 in. down to 90,000 volts per in. for conductor diameters of 0.65 in. All results, however, pointed to the correctness of an idea advanced some years earlier by Steinmetz; namely, that there exists a thin atmospheric zone adjacent to conductors that will endure greater electric intensities than the normal atmosphere beyond. A process was then found for locating the thickness of these zones beyond which the normal atmosphere would break first on the application of the corona forming electric intensity. The values of such critical electric intensities could then be estimated by the method illustrated in the following example:

Beyond the surface of a clean brass conductor 0.65 in. in diameter, the normal atmosphere broke into corona at a distance of 0.07 in., at a dielectric flux density of $170,000 \times 10^{-13}$ coulombs per inch cube. The coulombs per inch cube per volt established in the normal atmosphere are 2.244×10^{-13}.

It follows, therefore, that the volts per inch of electric intensity that ruptured the zone of normal atmosphere about this conductor was found to be

$$\frac{170{,}000\times 10^{-13}}{2.244\times 10^{-13}}=75{,}700,$$

a value that is in accord with the authoritative conclusion of leading physicists and that submitted above by Dr. Whitehead. This value of 76,000 was obtained for all sizes of conductor from 0.65 in. down to 0.2 in.; below that the results gave an increase,—from what cause was not determined. It may possibly be due to the lack of free ions emanating from the surface of the small conductor, or to some related cause.

As to the corona voltmeter mentioned by Professor Charters. It was made about two and a half years ago and has been used so far only for lecture work. It is heartily recommended to those who want to observe transient phenomena on high-pressure circuits, by direct vision or through a revolving mirror, for it is really also a sort of corona oscillograph. At this writing I am compelled to give the dimensions of the instrument and its range from memory. However, the values are throughout about right as given, because the recollection of them is clear.

The instruments consists of a tapered brass rod. 7 ft. long, $\frac{3}{8}$ in. diameter at the larger end and uniform for 1 ft., then tapering uniformly, to a diameter of $\frac{1}{7}$ in., at the opposite end. At the center of a 0.5 in. square galvanized steel wire net cylinder of the same length and 15.5 in. inner diameter, suitably insulated, the tapered rod is mounted. When put in the dark, and alternating pressure applied between rod and cylinder, the corona first appears at the small end of the rod, when ordinary barometric pressures and temperatures obtain, at about 25,000 effective sine-wave volts and extends the length of the rod as the pressure is elevated, reaching its full tapered length at about 55,000 volts. For greater ranges the dimensions must be increased in proportion or instruments of this size must be balanced in series across the circuit. It has not as yet been used in work of investigation. However, for some such purposes it will be useful.

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SURGES ON A CABLE SYSTEM WITH AN ALUMINUM SURGE PROTECTOR

EXPERIMENTAL INVESTIGATION OF THE SURGES ON AN UNDERGROUND ALTERNATING-CURRENT DISTRIBUTION SYSTEM, AND THE PROTECTION BY ALUMINUM CELLS

BY E. E. F. CREIGHTON AND S. D. SPRONG

The investigations referred to later in this paper were begun by the authors early in the summer of 1908 and covered a period of from eight to ten weeks. The system of the United Electric Light & Power Company, of New York City, seemed particularly desirable for this class of investigation, as it is the largest alternating-current light and power system that is entirely underground and therefore subject to the particular class of phenomena treated by the paper; moreover, it is without the variations that might be encountered in a system having a part of its lines overhead.

The system of the company does not differ substantially from others distributing alternating current underground, but as there are certain minor departures from the usual practice it may be desirable to give here a brief description, so that any small differences can be taken into proper account in a study of the application of the suggested solution to other systems.

The Island of Manhattan, over which the company's system extends, is divided into two approximately equal districts, which are operated independently north and south of Fifty-ninth street. More or less centrally located in either district is a sub-station supplied at 7500 volts, 60 cycles, three-phase, from the Waterside Station of the New York Edison Company. In the sub-station this current is stepped down by 2750-kw. air-cooled transformers to 2250 volts, two-phase, and is distributed on the three-wire, two-phase system. All the lighting load and about one-half of the power load are carried on the two outer primary conductors at 3000 volts, thereby nearly doubling the efficiency of the primary distribution and simplifying the question of feeder regulation, which resolves itself into the regulation of the voltage on the outer conductors only.

Each feeder carries an independent district of its own, aggregating about 800 kw. at the peak load. The feeder potential is regulated by an 85-kw., motor-operated, two-phase, air-cooled induction regulator. As only the two outer conductors of the feeder pass through the regulator, as shown in Fig. 1, its effect, as described above, is to increase or decrease the length of each side of the right-angle or quarterphase potentials. This arrangement gives a concentrated inductance in series with the capacity of the feeder, and it is at this point that the problem is met of protection from surge and other abnormal potentials. The potential regulator produces a constant potential of about 250 volts across its secondary, which gives a plus or minus regulation, depending on its phase-angle with the main electromotive force. This phase-angle is regulated by the mechanical movement of the motor-operated primary. The constant secondary potential is particularly suited to the application of the aluminum by-pass cells, as will be described later.

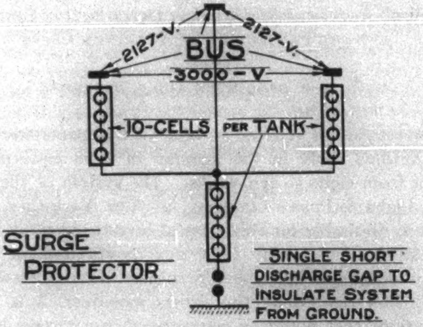

FIG. 1—Connections of the surge protector to the bus bars

The operating experience of the United Electric Light & Power Company, covering a period of some years, has frequently indicated the presence of abnormal potentials which were evidently due to surges. This was shown by punctures on other cables occurring simultaneously or shortly after the grounding of some one feeder. Breakdowns, which usually follow the grounding of a feeder, sometimes happened in one or more of the feeder regulators. This was due, as will be explained, to what may be called the banking up of the potential against the regulator on the feeder side of its reactance.

The total amount of primary cable connected to the bus-bar of each sub-station was about 170 miles during the period of test. This mileage of cable was divided into 14 approximately equal and independent sections, each supplied by a three-conductor feeder on the radial system; that is, the network of primary distributing conductors covering a particular district, is supplied at its approximate load center by a three-conductor feeder direct from the sub-station bus-bar. The capacity current per feeder with its distributors is about 2 amperes per leg, and this capacity, in series with the high reactance of the induction regulators, gives a combination that is dangerous under a wide variety of disturbances.

It may occasion surprise to some that any company would deliberately undertake the hazard of causing surges on its working system, but in considering this point, it should be kept in mind that the United company has the largest alternating-current system that is entirely underground and, therefore has been among the first to observe the results of the phenomena involved and felt compelled in the absence of any other source of reliable information to resort to a practical investigation on its own system. It was decided that, because of the frequency of breakdowns and the variety of conditions under which they occurred, the point was being reached when to prevent the conditions becoming still more acute the case needed not so much a desperate remedy as an extreme method of diagnosis While the method adopted was no doubt radical, it seemed the only possible way to attack the problem with any chance of satisfactory results. The experimental work was undertaken with caution, in that but one step in the dark was taken at a time after which all the data were correlated, including the development of the oscillograph film, so that the drift of the experiment could be checked before the hazard was multiplied further.

It seems hardly necessary to add that these precautions included the application of the aluminum surge protector to the bus-bars at all times, as shown in Fig. 2, and also the use of needle gaps at different points of the system in an endeavor to indicate potentials before they became hazardous. Earlier experiences of the company while operating the uptown and downtown systems in parallel, showed a more extended damage to other feeders when one developed a fault. This bears out the results of the tests showing that extensions of the system lower its natural frequency to such a value as to bring it within the range of the harmonics of the generator. While the expedient of separating the whole distributing network into two districts postponed the possibility of resonant troubles, the system is a growing one, and as further division is not advisable it was necessary to consider the possible extension of some one district to the point where the frequency would come within the range of the usual generator harmonics. The problem lay in either keeping a high natural frequency of the system by subdivision or using some means of absorbing the energy of abnormal potentials.

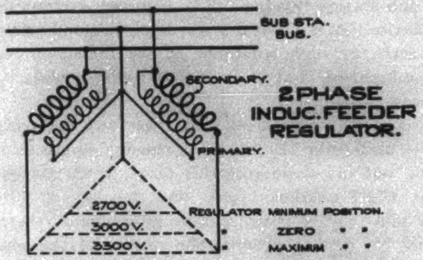

Fig. 2—Connections of the induction regulator

Generally speaking, all alternating-current distributing systems require individual feeder regulation. As any form of regulator must involve reactance, it follows that there will always be the probability of abnormal and often dangerous potentials, as a result of the feeder capacity and regulator reactance. This brings us, then, to the necessity of either taking care of the excess potential on the feeder side of each regulator individually, or by-passing it around the regulator to the station bus-bar, thus making it possible for a single protective equipment to take care of all feeders.

The latter method is preferable, as it reduces to a minimum the investment and bulk of equipment to be provided for in the station. It also provides a way to locate instantly the particular feeder in trouble. As a third advantage, it prevents the piling up of the surge potential on the end-turns of the regulator coils. A further advantage is that by-passing the reactance of the regulator very greatly increases the frequency of the surge and therefore raises it above any possibility of resonance with any of the generator harmonics.

It should be noted in this connection that by-passing a reactance with an aluminum cell almost entirely eliminates such reactance from the circuit. It is for this reason, as described below, that the frequency of a feeder goes much higher than the range of the oscillograph. In other words, by the elimination of the reactance by means of the aluminum by-pass cells, the feeder then oscillates at its natural frequency and the concentrated reactance of the regulator becomes an insignificant factor in its period. It is quite possible that this principle may be employed for other uses than the one covered by this paper.

The first series of tests were carried out with the use of one cable only and its potential regulator. The natural frequency of oscillation, due to a grounded phase through an arc, was of the order of 3000 cycles. Knowing the capacity of this cable, the inductance to correspond to this frequency was calculated and was found to be in the neighborhood of 0.001 henry. This low value of inductance shows that the inductance of the distributing transformers on the circuit with open secondaries is not a factor in this oscillation, since the value of such inductance would be many times greater than the requisite value. The inductance calculated by a short-circuited regulation from tests on the potential regulators gave the value desired of about 0.001 henry. In other words, the oscillation recorded by the oscillograph shows that the energy of the static charge of the cable passes into electro-magnetic energy in the potential regulator and is re-transformed from one to the other until dissipated.

Later tests were made with an increasing number of feeders from the same bus-bar. It was found that the natural frequency of oscillation, as recorded by the oscillograph, diminished with each additional feeder. With twelve feeders on a circuit, the natural frequency of oscillation had decreased from about

1800 to 680, which is about eleven times the generator frequency. In other words, this system of twelve feeders would resonate with the eleventh harmonic of the generator wave if such an harmonic existed. The potentials across the line coil of the potential regulator showed increasingly higher values as the number of feeders on the system was increased. So far as the oscillograms show directly, these values of surge potential reached the dangerous zone.

By indirect calculation it can be shown that the natural frequency of a cable oscillating by itself may be as high as 25,000 cycles, and such a frequency could not possibly be shown by the oscillograph since the natural frequency of an oscillograph is seldom over 8000 cycles. On careful examination of the oscillogram it is found that the initial deflection when the surge takes place is as instantaneous as the inertia of the moving part of the oscillograph can record. In other words, the discharge from the cable strikes the end-turns of the potential regulator and piles up the potential there. Subsequently the surges "ooze" through the inductance of the regulator and produce thereby a lower frequency at potentials, which, for the simple grounded phase, are less hazardous to the total insulation of the regulator.

What may take place when a grounded phase combines with a short-circuit, as frequently happens, is impossible actually to test, but there is every reason to believe that the potentials will reach a far more dangerous total value across the coils of the potential regulator. The evidence seems to point to the conclusion that the grounded phase does not instantly damage the end-turns where the surge potential piles up, but that the injury is caused by long-sustained surges. Each surge probably causes a small amount of sparking between turns of the coil or between layers, and the dynamic potential difference across the spark is not sufficient to maintain an arc. Each one of these spark discharges probably causes some disintegration of the insulation between turns or layers, and it is only after continued stresses of this kind that the trouble develops gradually into a short-circuited condition of the turns of the potential regulator.

The best means of protecting the potential regulator will be to apply aluminum cells across the regulator coils. This was done in the test, and the oscillogram of the current in the cells circuit showed a maximum rise of over 50 amperes from a normal current of about 0.1 ampere. This test was made with a current transformer in series with the cell, which in itself reduces the natural frequency through the cell circuit. Observations on the cells, without the current transformer in circuit, showed an unusual activity. In fact, never in any test made in the laboratory or in service have the plates shown an equal amount of luminosity on the surface nor have they given out as loud a sound.

OSCILLOGRAPHIC RECORDS.

General comments. While these records are very clear in the film, it is found impracticable to obtain good reproductions unless the curves are intensified. Where so many high-frequency waves appear, the most practicable method of intensification is by means of a pen and ink working under a magnifying glass. In these records this inking has been done with care, although without the engraver's experience. In general the ink lines follow the records. Two things are lost by inking: first, occasionally on the waves are higher harmonics which can be shown only by the fine lines of the record; secondly, due to unsteadiness of the hand and width of ink line, a record of an almost instantaneous change, which appears as a thin vertical line, loses this definiteness. These refinements of analysis are in general not important. Some of the lost effects will be referred to in particular in the comments on individual oscillograms.

The oscillograph used in these tests had three vibrators. It will aid in studying these oscillograms to know that two of the vibrators were, with few exceptions, kept in the same part of the circuit. The vibrator giving the middle record was placed between a phase and ground and was maintained in this position in every case where a ground was produced. The last two oscillograms shown, Figs. 23 and 24, are the only ones without a ground. The vibrator giving the lower record was placed in the ground leg of the surge protector, except in Fig. 13. The vibrator giving the upper curve was placed successively in different positions; viz., potential of bus-bars, potential between line and ground, and across the coils of different regulators; both on the grounded phase and the non-grounded phase. In most cases only one factor was changed at a time. These relations are brought out in the *List of comparative oscillograms* given later.

The three wires of Fig. 2 are named as follows: A_2 the middle wire, and B_1 and B_2 the outer wires.

Fig. 3 shows the general connections for test. Under each oscillogram the specific connections are given. Cable No. 109 was grounded in every case except those of the last two records. In these two, Figs. 21 and 22, cable No. 126 was grounded. In all the tests on No. 109, B_2 phase was grounded, but in the tests using cable No. 126, B_1 phase was grounded.

Needle gaps with series fuses and a resistance sufficient to limit the dynamic current to 0.5 ampere, were placed across both the bus-bar and the cable that was grounded. The object of these gaps was to record any possible peaks of potential that were too short in duration to affect the oscillograph. The line potential was 3000 volts and the gap-length equivalent to 6250 volts, but in no case during the test did the gaps spark over. These needle gaps will be referred to again later under the heading *Oscillations under normal operations*.

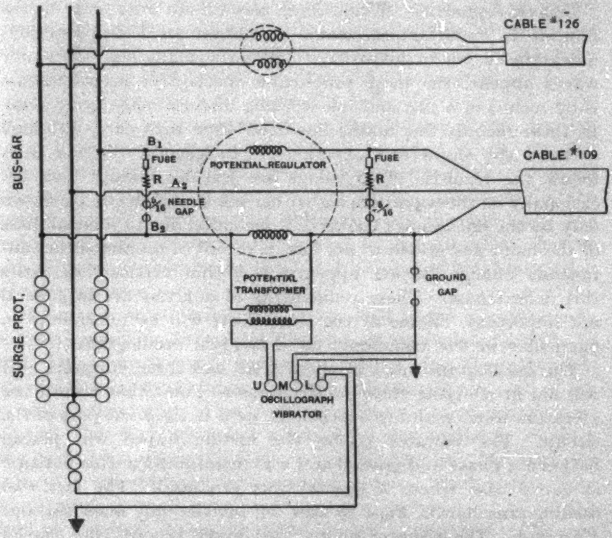
CABLE #126
BUS-BAR
B_1
FUSE
POTENTIAL REGULATOR
FUSE
CABLE #109
R
A_2
R
$\frac{5}{16}$ NEEDLE GAP
$\frac{5}{16}$
B_2
POTENTIAL TRANSFORMER
GROUND GAP
SURGE PROT.
U M L
OSCILLOGRAPH VIBRATOR

FIG. 3—The general connections of the circuit

In Fig. 4, oscillogram 504, with only cable 109 in circuit,

B_2 leg is grounded through an arc. The middle record shows this current. The rise of current was 68 amperes, although the capacity current is normally only about 2 amperes. This current oscillates during three half-waves of the natural period of the circuit. The gap between line and ground was set at its maximum sparking value and, furthermore, there seemed to have been some rectifying action at the gap which was sufficient to prevent the sparking of the gap when the generator wave reversed. This gives a discharge only at every second peak value.

FIG. 4

The upper record is the potential across the B_2 coil of the potential regulator. This is the leg that is grounded. Owing to the mechanical position of the regulator, its zero potential corresponds to the maximum across the phase; therefore the discharge occurs near the zero value of the potential of the regulator. There is a sudden rise of 384 volts, which oscillates for three half-cycles corresponding to the current to ground. This frequency is approximately 1800 cycles per second. After the arc to ground is extinguished, the system continues to oscillate but at a higher frequency; namely, 3000 cycles per second. This point is shown at *a* and *b*.

The lower record in Fig. 4 is the current through the aluminum surge protector to ground. It shows at *b* two rates of vibration the same as the voltage wave. After the second oscillation ceased, the current continued to flow to ground through the surge protector as shown at *c*. The arcing ground reduced the B_2 leg to ground potential and thus left the system out of symmetry with the zero potential of the ground. Since the surge protector was the only connection to ground, it carried the quantity of electricity necessary to charge up the ground phase. This change took place through a half-cycle of the generator wave and is shown at *c*. The first half-cycle of the discharge through the surge protector took a longer time than the second half-cycle. This is not true of the oscillations through the regulator coil on the upper record.

One of the characteristics lost in printing is in current discharge through the surge protector. The current starts very abruptly but on reaching 1.35 amperes, stops and recedes a little and then increases more gradually to its peak value of 5.4 amperes. This perhaps is due to the nature of the circuit. At the place where the cable is grounded, on one side is the distributed capacity of the cable and on the other side the inductance of the regulator. The different parts of the system have different rates of discharge due to their natural frequencies, and at any one point these discharges may be moving in opposite directions. Apparently this condition gives the variation in discharge through the surge protector. When more cables are added the results are sufficiently pronounced to be seen. The lower record in Fig. 14 with three cables connected to the bus-bars shows two distinct loops in the rise of the current in the surge protector. In the middle record showing current to ground, there is a hook in the wave of the first half-cycle just after the peak value is reached. When more cables are added this hook disappears.

Fig. 13 shows that the potential across the potential regulator recorded by the oscillograph is not the potential on the end turns, but is less.

In the first set of tests (oscillograms 500 to 517) the arc was produced by opening a knife-switch by hand. In the remaining tests a screw gap was used in an endeavor to produce an arc of constant length. The movement of the screw was controlled by cords attached to an arm and its travel limited by adjustable stops.

In Fig. 5, oscillogram 505, upper record, with one cable in circuit, B_2 leg is again grounded, but the potential is now measured across the B_1 phase of the same regulator. The middle record is the current to ground and the lower record the current in the surge protector. The latter two are identical with the previous oscillogram but the upper record differs in the following particulars:

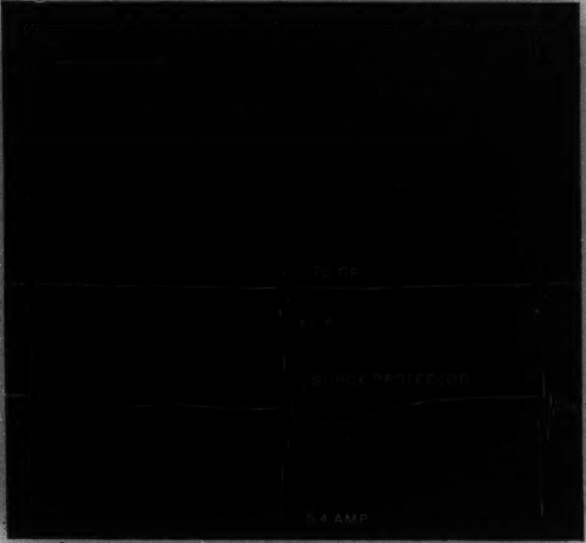

FIG. 5

1. This regulator coil is in the other phase of the two-phase circuit and, therefore, with the same mechanical position of the regulator, the potential must be either 90 degrees ahead or

behind; therefore, the discharge takes place during the peak value of the potential across the regulator.

2. The currents in the B_2 coil (Fig. 4, oscillogram 504) and the B_1 coil (Fig. 5, oscillogram 505) are in the opposite directions. In Fig.4 the surge potential rises with the rising potential across the regulator coil; but in Fig. 5, the reverse is true. Before the ground took place the B_1 phase was approximately 1500 volts effective above the ground, but after the B_2 leg was grounded this potential of B_1 was about 3000 volts above ground. The quantity of electricity to do this was taken through the regulator coils.

FIG. 6

3. The symmetrical form of the main wave in oscillogram 505 is destroyed by the oscillations. A mean line drawn through the oscillations shows a total drop from the main curve which is not recovered until after the oscillation ceases.

In Fig. 6, oscillogram 506, with one cable in circuit, the same circuit conditions exist as in Fig. 5; viz. the upper record shows the voltage across the B_1 coil of the regulator, the middle record shows the current from B_2 to the ground and the lower record shows the current in the surge protector. The changes are as follows: The scale of the potential wave has been altered to give a smaller record and the gap length between B_2 and the ground is shorter than in the previous test. In consequence of the smaller gap the phase is grounded more frequently and the potential across the gap at the instant of discharge is correspondingly less.

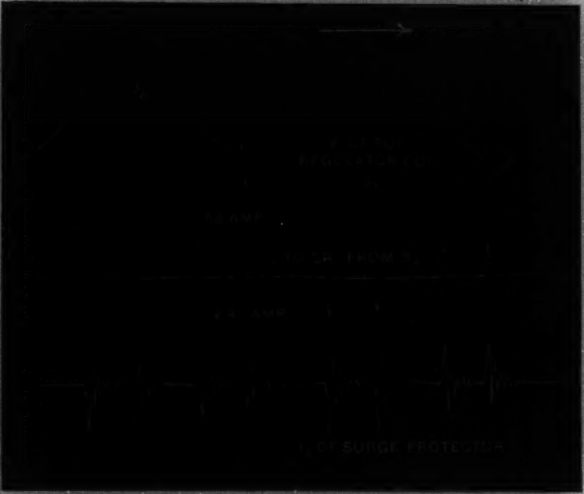

Fig. 7

Fig. 6, oscillogram 506, shows that the distortion of the wave of potential across the B_1 phase of the regulator depends on the condition of the charge of electricity left by the arcing ground. Compare the number of half-waves and the height of the final half-wave of each of the oscillations in the middle record with the corresponding disturbance in the potential record.

In Fig. 7, oscillogram 507, with two cables in circuit, the arc length is about the same as in the previous oscillogram, the only change being in the increase from one to two cables. This oscillogram does not lend itself readily to the calculations of frequency. The following values are given, however: The time of discharge to ground is represented by 1 m.m. equal to 1/2450 second, to which the time of discharge through the surge protector corresponds. Assuming that this wave is not greatly distorted, the frequency should be about 1225 cycles per second. After the ground arc breaks, the remaining oscillations are about doubly rapid; namely, 2450 cycles per second.

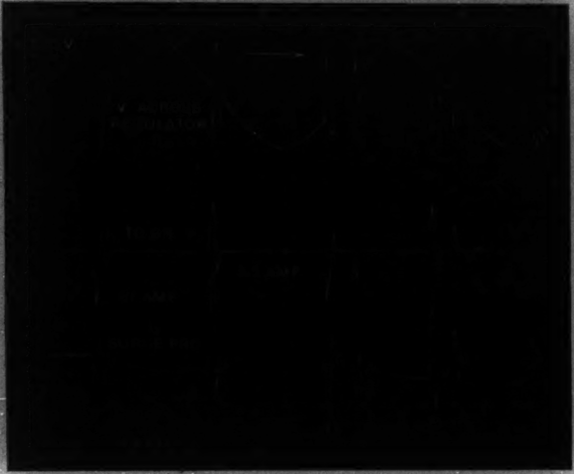

Fig. 8

By the addition of the second cable, little change has been made in the surges. What little change there was lowered the surges. This is shown by the lesser discharge through the surge protector.

In Fig. 8. oscillogram 508, with two cables in circuit, the only change made from the previous test was the transference of the potential vibrator from the B_1 phase to the B_2 phase of the regulator. Inadvertently the arc was a little longer, and in consequence the surge currents were greater and the occurrence less frequent. It is important to note that although the surge current to ground increased from 68 amperes to 97 amperes—only 42 per cent—the surge protector was required to discharge 4.5 amperes, an 82 per cent increase, comparing oscillograms 507 and 508 Figs. 7 and 8.

Except for the difference in arc length and scale for the upper record, Fig. 8, is comparable to Fig. 4, where but one cable was in circuit.

In Fig. 9, oscillogram 509, with two cables in circuit, the circuit connections are the same as in the previous test, but the arc to ground is made of short length. This results in a more frequent discharge to ground; in fact the frequency of discharge is about seventeen times the frequency of the circuit. This is noteworthy and is commented upon later, under the heading of *Artificial Harmonics*. Other than the danger of resonance these surges are less harmful than those due to longer arcs. Fig. 9 is comparable to Fig. 8 for the effect of long and short arcs to ground.

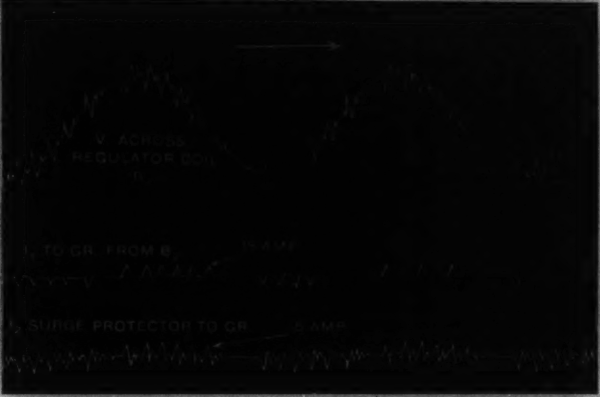

Fig. 9

In Fig. 10, oscillogram 510, with three cables in circuit, the circuit conditions remain the same; namely, voltage across

B_2, coil of the regulator, current to ground, and current through the surge protector. For a comparison of the effect of increasing the number of cables, Figs. 4, 8 and 10 may be used. The general effect is an increase in current to ground and maximum potential across the regulator, but, due apparently to the lower frequency, the surge protector is not called upon for a corresponding increase in discharge.

One cycle of the discharge to ground takes place at the rate of 1120 cycles per second. As closely as can be measured, the frequency after the arc to ground ceases is about double this; that is, 2240 cycles per second.

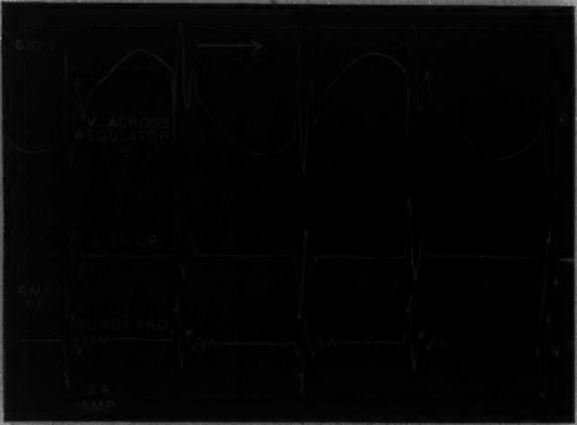

Fig. 10

In Fig. 11, oscillogram 511, with four cables in circuit, the circuit conditions remain the same as in Fig. 10. The voltage rise across the regulator coil and the current to ground have again increased over the condition of three cables. In this case the current in the surge protector has also materially increased. With the increase in current to ground there is a marked tendency for the arc to hold over more than a half cycle. From another standpoint this is a dangerous feature, as it allows of a longer arc—if the arc length were variable—which would produce a heavier surge. The approximately measured frequency is now 920 cycles per second for the oscillation to ground and, as near as can be measured, double this when the ground connection is broken.

In Fig. 12, oscillogram 514, with four cables still in circuit, the potential vibrator has been transferred to the grounded B_2 leg of another (No. 126) regulator. The other conditions remain the same as in 511 (middle record current to ground and lower record current through surge protector.) Oscillograms 514 and 511 give a comparison of the surges in two regulators when the cable of one is grounded. In this case the surges in the grounded potential regulator are more than ten times as great as in the other regulator. Aluminum by-pass cells had been placed across the coils of the grounded regulator No. 109; subsequently the fuse in series with the by-pass cell in the grounded phase was found melted. It is unknown whether this

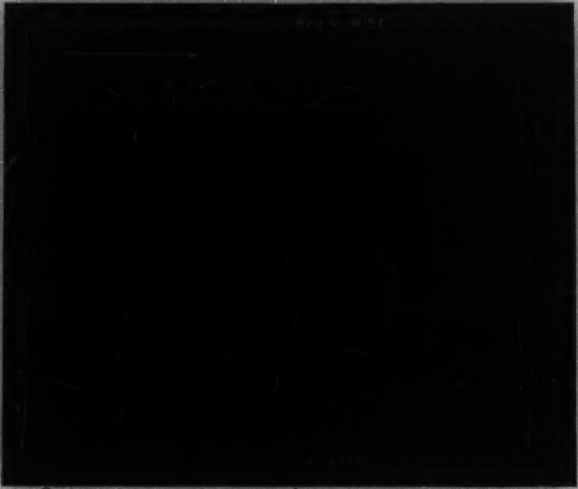

FIG. 11

took place before or after the oscillogram was taken; presumably it fused before the exposure.

The greater values of current in the two lower records of 514 are due probably to a slightly greater length of arc between the line and ground.

In Fig. 13, oscillogram 516, four cables are still in circuit. The potential is again across the grounded phase of the non-grounded regulator. The middle record is the current to ground. The vibrator on the lower record, however, has been changed. An aluminum by-pass cell shunts each side of the regulator (109) that is grounded; in series with the cell in the grounded phase B_2, a current transformer is placed, the secondary of which gives the lower record. Since the natural frequency of the cable with its regulator shunted must be extremely high (over 20,000 cycles per sec.), the oscillograph, with its own period of only 5,000 to 8,000 cycles per sec., cannot be expected to follow faithfully the variations in the circuit.

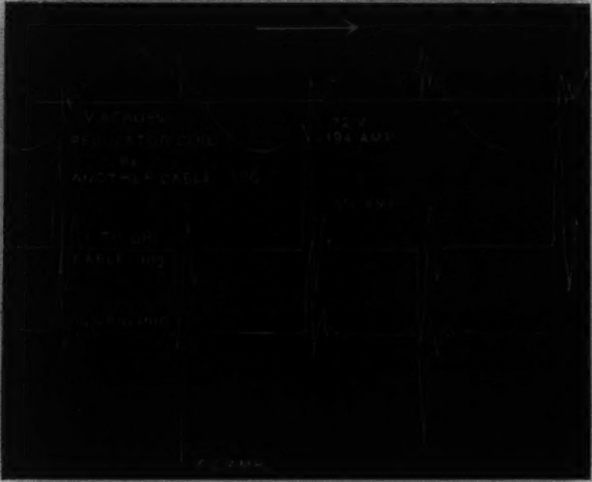

FIG. 12

The inaccuracies of the vibrator will consist in falling short of the maximum current; but in spite of this it is sufficiently surprising to get a record of 57 amperes in the cell. Another feature is the form of this current wave. The current rises rapidly to a peak value, descends as rapidly, crosses the zero, rises to a considerable value in the opposite direction—all before the current to ground has completed its first half-cycle, and maintains a flat top wave before it again reaches zero.

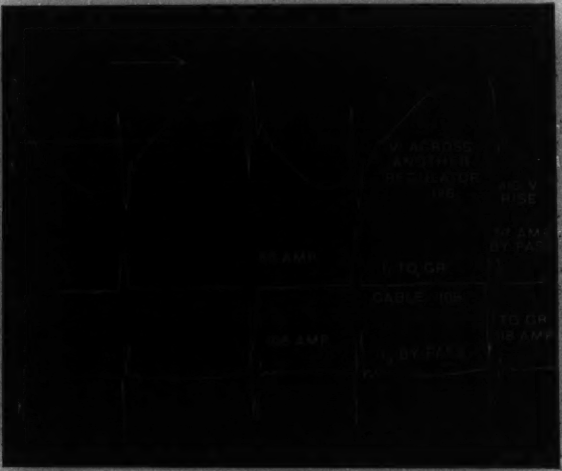

FIG. 13

The potential across the regulator (126) now takes a larger proportion of the total surge.

Another noteworthy condition in this record of current to ground is that the arc is extinguished at the end of the first half-cycle. The only reason apparent for this briefer duration is the presence of the by-pass cells.

In Figs. 14 to 20, seven oscillograms are shown which were taken three days later. The first four, 517, 518, 519, 521, were taken with three cables in circuit with different position of the potential regulator. The last three, 524, 526, 530, of the seven were taken with an increasing number of cables in circuit.

The conditions then for 517 are: three cables in circuit. The upper record is the potential between phase and ground of the grounded phase; in other words, the potential across the arc to ground. The middle record is again the current to ground. The vibrator giving the lower record is changed back to the usual position; namely, current in the ground leg of the surge protector.

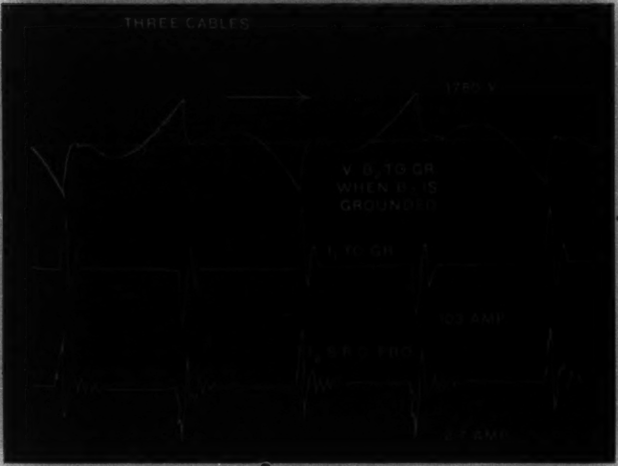

Fig. 14

Commenting on the oscillogram, it may be said that the potential across the gap rises normally to 1780 volts, which is the spark potential; it then drops quickly, but not instantly, to zero, and oscillates slightly across zero while the arc plays. After the arc goes out, the system gradually assumes its normal symmetrical condition of potential, and thus continues until the next arc takes place. (Due to faintness of the lines, one loop of potential was erroneously inked in above the zero. By comparison with the upper record this error will be evident.) The current to ground shows the usual form of discharge, but the current in the surge protector shows *two* distinct halts in rising to its peak value in the first half wave. This same form was shown in oscillogram 510 with three cables in circuit.

In Fig. 15, oscillogram 518 is directly comparable to oscillogram 517 in Fig. 14. The potential vibrator is now between the other phase B_1 and ground. Since this phase is 90 degrees from the grounded phase B_2, and since it takes a charge from the earth corresponding to the increase of potential above the earth, the wave-form is entirely different from both oscillograms 517 and 510, in Figs. 14 and 10, respectively.

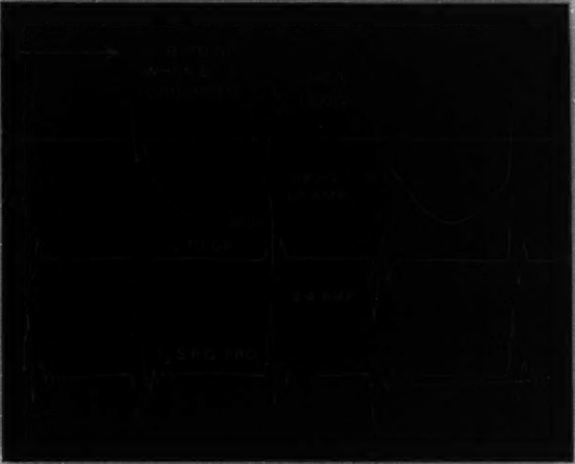

Fig. 15

The potential change of the non-grounded phase does not reverse during the first half-cycle of discharge to ground, as it always does *across* the grounded coil of the regulator. The potential of the non-grounded phase gradually changes in one direction so long as the current to ground is in one direction, regardless of whether it is increasing or decreasing, but the potential across the regulator coil has the form of a potential induced by electromagnetic transformation.

The maximum potential in the negative direction is 3000 volts and in the positive direction is 3660. The maximum possible is 3000 × 1.4 = 4200 volts. Any value less than this is due to the fact that after the grounded arc is extinguished the system has not time to regain its symmetrical relation of potential to the ground, which is 4200 volts maximum.

In Fig. 16, oscillogram 519, the records are directly comparable to those in Figs. 14 and 15. The disturbance in the potential wave between the two phases B_1 and B_2 during the grounding period is noteworthy. Although this disturbance appears relatively unimportant, it is actually a rise of 850 volts corresponding to the voltage added by the surge through the regulator.

FIG. 16

In Fig. 17, oscillogram 521, the records are directly comparable to those in Fig. 16. The potential is now taken across B_1 to B_2 on the bus-bars where the surge protector is connected. The disturbance in the potential wave, during the period of grounding, is reduced to about one-third the surge potential across the phases of the cable.

In Fig. 18, oscillogram 524, five cables are in circuit. The records are, respectively: voltage across the regulator coil of the grounded phase B_2; current to ground; and current in the surge protector to ground. The maximum voltage rise is 407 volts; the first peak value of the current to ground is 111 amperes; and the first peak value of the current in the surge protector to ground is 1.7 amperes. This oscillogram is comparable especially to others with a lesser number of cables in circuit.

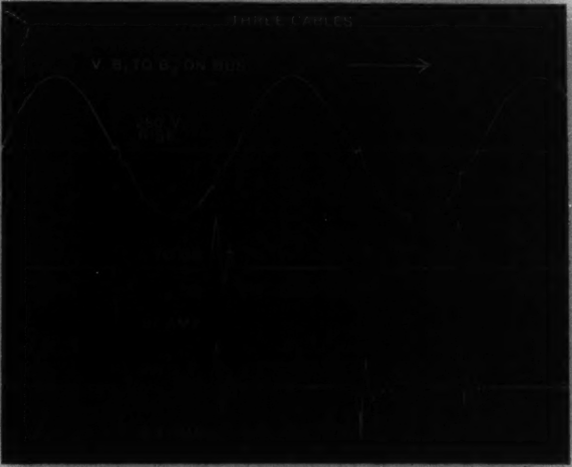

Fig. 17

Making calculations of the natural frequency from the middle record—the current to ground—the following values are obtained.

From	the	first half-cycle	725	cycles	per sec.
"	"	second "	1000	"	" "
"	"	third and last "	690	"	" "
"	"	first complete cycle	875	"	" "

The last value is the one used in previous measurements and the one which seems correct to use for comparisons. When not grounded the system oscillates with a frequency about twice as great; viz., 1740 cycles per second.

In Fig. 19, oscillogram 526, six cables are in circuit. The records are, respectively: voltage across the regulator coil of the grounded phase B_3; current to ground; and current in the surge protector to ground. The maximum voltage rise is 615 volts; the corresponding maximum current to ground is 175 amperes; and the corresponding maximum current in the surge protector is 2.4 amperes. This ocillogram is comparable especially to others with a lesser number of cables in circuit. The addition of this cable—No. 120— brings down the measured frequency comparatively little; viz., 875 to 855.

FIG. 18

In Fig. 20, oscillogram 530, seven cables are in circuit. The records are respectively: voltage across the regulator coil of the grounded phase B_3; current to ground; current in the surge protector to ground. The maximum voltage rise is 484 volts; the corresponding maximum current is 135 amperes; and the corresponding current in the surge protector to ground is 1.4

amperes. These maximum values were affected by the arc length, which was not always the same.

Again making detailed calculations of the frequencies represented by the discharge current to ground, the following values are obtained:

From the first half-cycle	645	cycles per sec.	
" " second "	990	" "	"
" " third and last "	590	" "	"
" " first complete cycle	844	" "	"

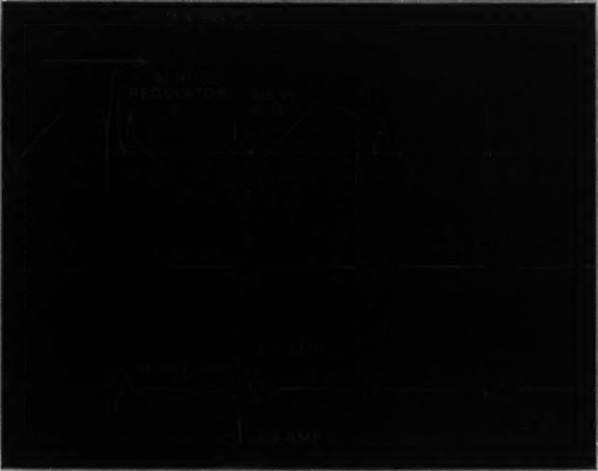

FIG. 19

The last value corresponds to the one used in the previous measurements.

In Fig. 21, oscillogram 576, four cables are in circuit. The next two oscillograms shown were taken one week later. Instead of cable 109, cable 126 was grounded. The records are, respectively: voltage across the regulator coil of the grounded phase B_1; current to ground; and current in the surge protector to ground. The maximum voltage rise is 520 volts; the corresponding current to ground is 92 amperes; and the corresponding current in the surge protector is 1.4 amperes. The estimated frequency is less than 1290 cycles per second—taken from a cycle of the current in the surge protector.

In Fig. 22, oscillogram 582, twelve cables are in circuit. The records are, respectively, voltage across the regulator coil of the grounded phase B_1 of cable 126; and current to ground. In this oscillogram a new shunt on the vibrator in the surge protector circuit gave a deflection too small to reproduce. The maximum voltage was over 1080 volts across the regulator, which carries normally 250 volts effective. The current to ground was 336 amperes maximum.

FIG. 20

Again making detailed calculations of the frequencies represented by the discharge current to ground we have:

From the first half-cycle	545 cycles per sec.
" " second "	870 " " "
" " third "	500 " " "
" " first complete cycle	670 " " "

The two oscillograms, shown in Figs. 23 and 24, were taken on a single generator on another system, that of the Brooklyn Edison Company, and are reproduced through their courtesy.

This generator wave shows very strongly the superposition of higher harmonics. Fig. 24 shows the current and potential of the same generator as in Fig. 23 when the generator is attached to the cable system. The capacity so magnifies the harmonics that they predominate over the fundamental. The principal harmonic is the thirteenth, corresponding to N ± 1 teeth; *i.e.*, twelve teeth per pair of poles.

Fig. 21

The oscillogram in Fig. 24 is reproduced to illustrate what resonant conditions might develop. If this generator produced 60 cycles the frequency of the thirteenth harmonic would be 780 cycles per second, and would resonate when placed on a system with conditions equivalent to those of the United Electric Light & Power Co. with eight cables in circuit. This is a graphical illustration of the dangers that may attend the variation or extensions of any electrical transmission system.

Notes. Not all long arcs are necessarily the same length. An endeavor was made to maintain a constant length, but due to inequalities in the crater rims some variations occurred; therefore, there will be corresponding variations in the current and potential values independent of the other controlling factors, such, for example, as the number of cables in circuit.

In brief, the tabulations tend to show the following:

1. A gradual decrease in the natural frequency of the circuit as the number of cables in circuit is increased—see the following tabulation and Fig. 26.

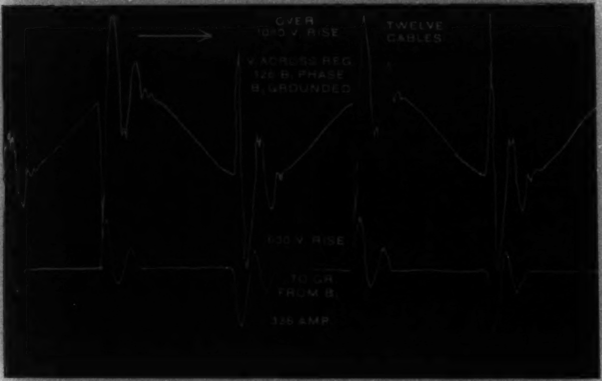

FIG. 22

2. An upper limit of three half-cycles of current from the grounded phase to ground, which was limited probably by the length of arc combined with the value of current and the value of natural frequency relative to the generator frequency. There are fewer numbers of half-cycles than three for shorter arcs.

3. A general increase in the current through the arc to ground with an increase in the number of cables.

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* The authors are indebted to Mr. R. H. Marvin for manipulating the oscillograph.

TABULATION OF GENERAL OSCILLOGRAPHIC DATA
THE GROUPINGS BY HORIZONTAL LINES CORRESPOND TO DIFFERENT DATES
(FOR MORE COMPLETE INFORMATION OF THE CIRCUIT CONNECTIONS THE PREVIOUS DETAILED NOTES SHOULD BE CONSULTED)

Fig. No.	Oscillogram No.	No. of feeders	Frequency to ground	Half cycles to ground	Current to ground	Current in surge protector	Maximum voltage rise	Relative arc length	Discharges per cycle		
4	504	1	1800	3	68	5.4	384	Long	1	Voltage across regulator coil (B_2) grounded phase	(*A*)
5	505	1	1800	3	68	5.4	247	"	1	" " " " Non-grounded "	(*B*)
6	506	1	....	1–2–3	58	3.1	148	Medium	4	" " " " "	"
7	507	2	1225	1–2	68	2.45	70	"	4	" " " " " "	"
8	508	2	1225	1–2–3	97	4.5	520	"	4 2	" " " " Grounded "	(*A*)
9	509	2	....	1	19	0.5	84	Short	12	" " " " " "	"
10	510	3	1120	3	116	2.4	630	Long	2	" " " " " "	"
11	511	4	920	3	170	4.1	820	"	2	" " " " " "	"
12	514	4	....	3	194	5.4	72	"	2	Another regulator and cells.	(*C*)
13	516	4	....	1–2	106	(57.)	410	"	2	(*C*) and *I* by-pass.	(*D*)
14	517	3	....	3	103	2.7	Drop	"	2	Voltage between B_2 and ground when B_2 is grounded	(*E*)
15	518	3	1020	3	116	2.4	(3465)	"	2	" " B_1 " " " " " "	(*F*)
16	519	3	....	3	109	3.0	850	"	2	" " phases (B_1 and B_2)	(*G*)
17	521	3	....	3	97	2.3	280	"	2	" " " " " " on bus.	(*H*)
18	524	5	875	3	111	1.7	407	"	2	" across regulator coil of grounded phase (B_2)	(*A*)
19	526	6	855	3	175	2.4	615	"	2	" " " " " " " "	"
20	530	7	844	3	135	1.4	484	"	2	" " " " " " " "	"
21	576	4	....	1	92	1.4	520	Medium	4	(*A*) on other cable (*A'*)	
22	582	12	670	3	336	....	1100	Long	2	" " " " "	
23 24	554 556	Not directly comparable, see oscillograms.									

4. An increase in the current to ground with an increase of spark voltage to ground, which is controlled mostly by the gap length.

5. A variable duty required of the surge protector, which duty apparently depends on the suddenness of the discharge. In general, the duty between line and ground is lessened by addition of cables, but there are some notable exceptions.*

6. A by-pass cell on a potential regulator is called upon to give a high discharge in order to protect the regulator.

7. The maximum surge voltage across the grounded phase of a regulator coil is directly proportional to the maximum surge current to ground. (Although the ratio on different dates is not identical, each makes a straight line; see Fig. 25).

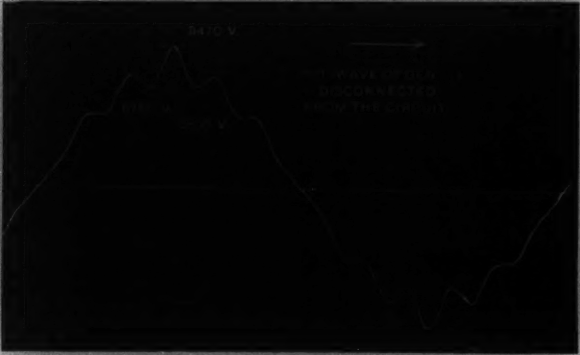

FIG. 23

8. The number of half-cycles of potential across a regulator coil is always one more than the number of half-cycles of discharge current through the arc to ground. This is explained by the fundamental law that the induced potential always opposes a change in the current. Therefore, as the surge current increases in the regulator coil, the potential is in the negative

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* Only surges to ground through the surge protector were measured. The surges from line to line during a disturbance are more severe since they will blow a 10-ampere fuse.

direction, but becomes positive as soon as the current begins to diminish.

9. The gap length determines the voltage, and therefore the current, of the static charge to the cable. The shorter the gap length, the greater the number of discharges for each alternation of the generator wave.

Relations between the frequency and number of cables. The frequency involves two factors; namely, the capacity and inductance. The capacity varies directly with the cable length, but the inductance depends upon four factors; namely, 1, the length of three-conductor cable; 2, the length of single-conductor cable; 3, the inductance in the regulator; and 4, the inductance in the transformers. In view of the difficulty of separating these factors in the several cables, the assumption is made in the curve shown in Fig. 26, that both capacity and inductance are proportional to the length of cable.

FIG. 24

Artificial harmonics. Impulses may be given to the circuit by the variation from a simple sine curve in the main wave—the harmonics—; or, secondly the circuit may get impulses either by electrostatic induction or electro-magnetic induction from an external source. Thirdly, from either of the above sources impulses may be given to the circuit by unbalancing the system relative to the normal neutral. Such an impulse comes from the accidental grounding of one phase through an arc. The arc forms every time the voltage across the gap reaches the spark value and is extinguished as soon as the current dies down. The frequency of the repetition of these impulses will depend greatly upon the length of gap, the conditions of capacity and damping, and the rate of change of potential. As already pointed out in the discussion of Fig. 9 the danger of these short arc frequent impulses or *artificial harmonics* lies in the possibility of their frequency coinciding with the natural frequency of some part of the circuit.

GUIDE TO FURTHER COMPARISON OF OSCILLOGRAMS.

To compare the effect of lengths of arc to ground use the oscillograms shown in Figs. 5 and 6, with one cable in circuit, or Figs. 8 and 9 with two cables in circuit.

TABLE OF OSCILLOGRAPHIC DATA RELATIVE TO THE NUMBER OF CABLES IN CIRCUIT

No. of oscillogram	No. of cables	Frequency grounded	Current to ground	Current in surge protected	Maximum voltage rise	Feet cable lengths
504	1	1800	68	5.4	384	38,700
508	2	1225	97	4.5	520	76,800
510	3	1020	116	2.4	630	130,400
511	4	920	170	4.1	820	179,400
524	5	875	111	1.7	407	216,200
526	6	855	175	2.4	615	263,600
530	7	844	135	1.4	484	301,300
576	12	670	336	....	1100	715,400

To compare the surges in the two phases of the potential regulator, that is, the grounded and the non-grounded phase, use Figs. 4 and 5, with one cable in circuit; also Figs. 7 and 8, with two cables in circuit.

To compare the voltage between phase and ground of the grounded and non-grounded phases, use Figs. 14 and 15.

To compare the surges between phases on the bus-bar side of the regulator to the corresponding surges on the cable side, use Figs. 16 and 17.

To compare the effect of the number of cables in circuit on the surges in the non-grounded phase of the regulator, use Figs. 6 and 7.

FIG. 25

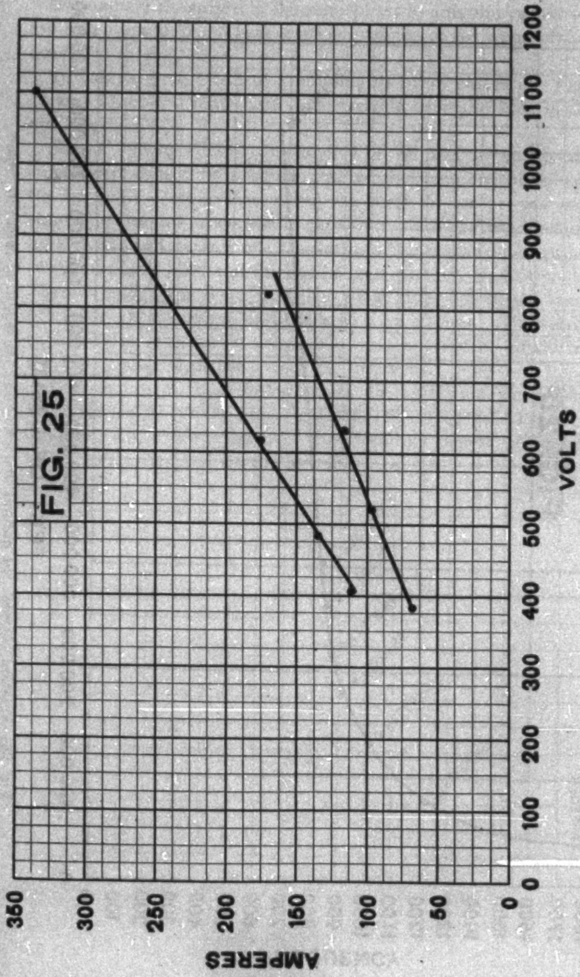

FIG. 25—Relation between the discharge current to ground and the simultaneous potential across a regulator coil

FIG. 26

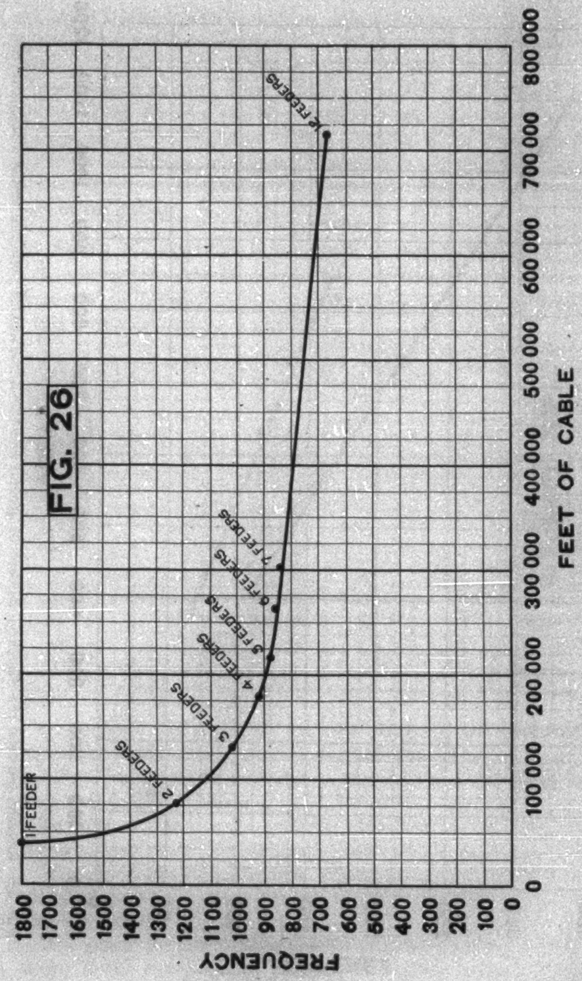

FIG. 26—Relation between the natural frequency and the length of cables in circuit

To compare the surges in the same phase in different regulators use Figs. 11 and 12. There is some question of the exact circuit condition in Fig. 12.

To compare the effect of grounding different cables use Figs. 11 and 13, noting that there is a variable between them in the arc lengths.

Surges during normal operation. In all the foregoing the surges were caused by producing an arc between one phase and the ground. During these tests the surge protector was constantly in circuit. Also needle gaps were placed between phases both inside and outside the regulator. The normal voltage between phases is 3000 and the needle gaps were set on 6250 volts. These needle gaps were installed some time before the surge protector was connected and the tests were started. The needle gaps sparked over twice before the tests but not at all during the tests, in spite of the heavy disturbances.

The sources of these disturbances during normal operations is the subject of further investigations. These surges have been observed on other systems. They seldom reach potentials much greater than twice the normal.

Discussion on "Surges on Cable Systems with Aluminum Cell Protection." Frontenac, N. Y., June 29, 1909

J. L. R. Hayden: To investigate how the aluminum cell protects apparatus against high-voltage disturbances, a number of oscillograms were taken, some of which are given in the following.

A standard 5-kw. lighting transformer, shown as *T* in Fig. 1, was connected, with its low-potential coil as primary, to the 60-cycle city supply of Schenectady, and high-voltage impulses were sent into the secondary . These high-voltage oscillations were produced by the discharge of a large mica condenser *C*, Fig. 1, through a series of reactive coils *x* and over a spark-gap *S*. An air-blast across the spark-gap *S* gave abruptness to the discharge. The reactances *x* were chosen so large as to bring the frequency of the discharge—about 1000 cycles—well within the range of the oscillograph.

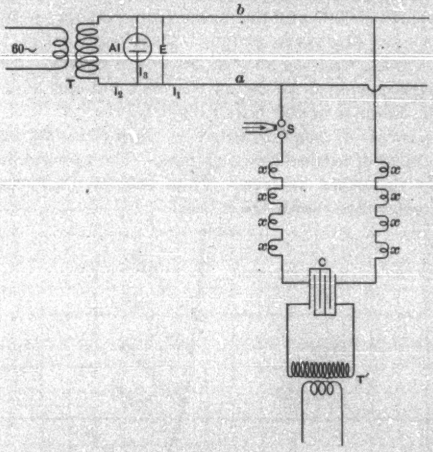

Fig. 1

The condenser C was charged by a 30,000-volt transformer *T'*.

As often as the voltage at the condenser *C* rises sufficiently high to break over the spark-gap *S*, it sends an oscillatory discharge or high-voltage impulse into the line *a b* and the transformer *T*, and the arrangement thus represents the condition of a step-up transformer continuously receiving high-voltage impulses from a transmission line (as by an arcing ground on the line).

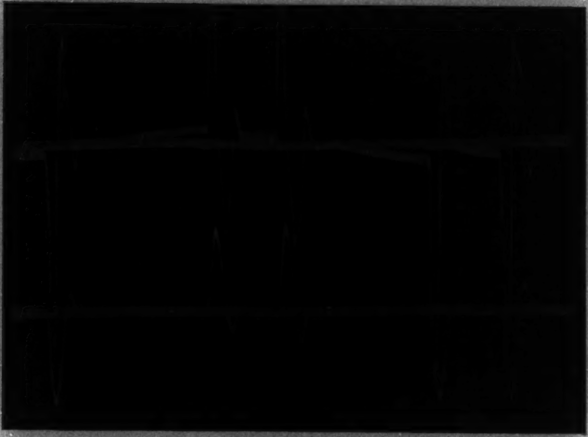

FIG. 2

FIG. 3

The oscillogram in Fig. 2 shows the voltage E at the transformer terminals, and the current I in the line and the transformer, without aluminum cell protection.

[Fig. 4

The low sine-wave in the upper curve is the normal 60-cycle voltage of the transforner, and the oscillatory impulses carry the voltage up to ten or fifteen times the normal value. Of this excess voltage much is probably concentrated at the end-turns of the transformer. In the lower curve, no 60-cycle sine-wave appears, as the secondary $a\,b$ of the transformer was not loaded. It is interesting to note here and in the following

Fig. 5

voltage oscillograms the appearance of higher harmonics in the wave-shape of the oscillations.

An aluminum cell was connected across the transformer terminals, at *a b* in Fig. 1. The oscillograms of voltage *E* and current *I*, under these conditions are given in Fig. 3.

The current impulse coming from the line *a b* appears unchanged, but the high voltage peaks of Fig. 2 have entirely disappeared, and only slight rounded kinks show where they would have occurred without the aluminum cell.

To see what becomes of the oscillating current *I*, oscillograms were taken of the current I_2 in the transformer and the current I_3 in the aluminum cell. These are shown in Fig. 4.

The entire current impulse passes through the aluminum cell, the lower curve in Fig. 4, while the transformer current shows only a very slight kink at these points, less even than the voltage curve in Fig. 3.

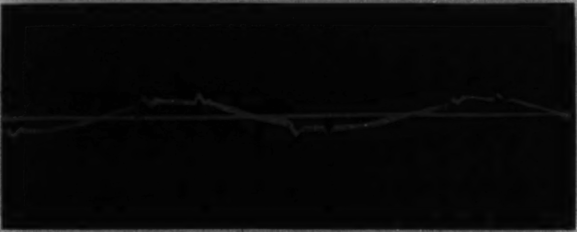

Fig. 6

Figs. 5 and 6 show oscillograms of the voltage *E* at the transformer, with and without the aluminum cell, the latter being shown on a larger scale. As will be seen, the enormous sharp voltage peaks entirely disappear owing to the presence of the aluminum cell. The latter thus protects the transformer without causing any disturbance in the system.

H. W. Fisher: Mr. Sprong has told me that he started these experiments with some misgiving. If he had obtained voltages approximating ten or fifteen times the normal voltage, as I believe Dr. Steinmetz predicted on some of the experiments on the Manhattan Railway cables, great damage might have been done to the system. We probably do not realize the risk taken in putting these surges and oscillations on the lines, and for a paper of this kind, giving the results of tests made for the purpose of observation to improve our systems and methods of operation, I think the Institute is especially indebted to the person and company who took that risk.

John B. Taylor: I think there is little question at to the effectiveness of the aluminum-cell arrester. It seems to be the closest we have come in electrical circuits to approximating the safety valve on the steam boiler. Doubtless while many improvements will be made in its form and the materials of which it is made, the idea seems to be distinctly the proper one for protecting electrical circuits from abnormal rises of potential.

I do not understand the basis on which is figured such a marked reduction in natural frequency of system, as the length of cable in circuit is increased, because I do not see readily what combination of cable and apparatus is taken to be oscillating. The natural frequency, of course, is determined by a combination of inductance and capacity, and it seems to me that the inductance would be more or less fixed by generators and transformers, while the capacity would increase as the number of miles of cable increased. This would tend to leave the inductance a constant figure with variable capacity, which would tend to increase the frequency rather than lower it as more cables are connected in.

Are not these men magnifying the dangers of operating an alternating-current system? Is an oscillogram of charging current with prominent thirteenth harmonic any evidence of narrow escape from a dangerous condition? The finest sine-wave found on any generator will pass to a condenser a current which is far from a sine-wave. If the thirteenth harmonic were a constant-potential affair; if the generators were constructed to give the thirteenth harmonic, and maintain it at constant potential irrespective of current drawn at that frequency, the matter might be serious, although resistance will always damp, and variable inductance of apparatus containing iron will always prevent, perfect resonance.

I have said before in discussing papers, that harmonics in alternating-current systems are interesting, but very seldom are they found to be the bugbear that some of us are inclined to think they are.

Ralph D. Mershon: Am I to understand that Fig. 23 is intended to show a voltage wave of the generator on open circuit? I am surprised to see such a ragged wave. I did not know that any modern generators had such a marked effect from the teeth.

E. E. F. Creighton: It is not a modern generator.

Ralph D. Mershon: That explains it. I should greatly appreciate it, and doubtless other members present would also, if one of the authors would give us some data relating to the latest form of the electrolytic condenser for this or other uses. How durable it is when continuously subjected to voltage? How durable it is if it is intermittently subjected to voltage of any sort? What are the details of construction so far as they are willing or able to give them, both from a mechanical and a chemical standpoint?

Charles P. Steinmetz: I believe I can answer Mr. Taylor's question, as to why the frequency decreases with increase of number of cables. The oscillating circuit is shown in Fig. 3, and consists of a system of from one to twelve feeders, each feeder with its potential regulator, and all connected in multiple through a single potential regulator to the ground; that is, the grounding arc, over which the oscillating current passes, contains in series first a single potential regulator, and then all the cables with their regulators. All these cables which their regulators in multiple would keep the same frequency, no matter how many cables, because the ratio of inductance and capacity remains the same, but as they are all in series with a constant inductance, the frequency increases with the decrease of number of cables, and the resultant frequency can be calculated from the number of cables, and the inductance and capacity, and checks well.

E. E. F. Creighton: Dr. Steinmetz has already answered the question relating to the variation in natural frequency. I might simply add that we gave no calculations at all on that subject. The results are all measurements. The matter which Mr. Taylor brings up, regarding the thirteenth harmonic disappearing, is worthy of still further comment. In Fig. 23 the oscillogram is shown first on open circuit, but the fact that a load is placed on that machine does not destroy the harmonic. There is always a possibility of getting the harmonic any time under the proper conditions, even though there be a great deal of power taken from the generator at the same time. The thirteenth harmonic may be brought out by the proper capacity and inductance relation, or by the proper length of arc connecting it to ground.

There have been a number of tests made of the effect of the length of arc on the frequency, and one laboratory experiment brought it out very clearly, without the aid of oscillograms. By placing an electrolytic condenser in series with the primary of the transformer, the amount of energy and voltage could be limited, Then, putting on the secondary side—the high-potential side—a spark-gap that could be varied, it was possible to open the spark-gap and get different musical notes at different lengths of arc, showing that the frequency—the artificial harmonic—actually does change with the length of gap.

In regard to the construction of the different aluminum protectors, there are three types at the present time, one that has been in use for some time, known as the gap-aluminum arrester consisting of nested plates. In that case there is always a gap in series, set at a voltage slightly above the line voltage, the minimum being, say, about 25 per cent above the line voltage. The length of time that any one of these arresters will operate depends entirely on the construction. The normal construction gives an operation of about 30 min. without any damage to the arrester. The lower voltage arresters, having a greater radiating surface, will operate for a long time without overheating.

A test was made on a 100,000-volt arrester, that being the maximum voltage in use, and the discharge was allowed to play for 40 minutes. The temperature rise at the top of the coil was about 18 deg. That type of arrester has been thoroughly tried out at the present time, and aside from slight changes, which will not affect the arrester in general, it is presumed at the present time that it is in a finished condition.

The second type of aluminum arrester is that used on direct current; that is, used without any series-gap. Where direct currents are employed the loss of energy in the film is very slight, and consequently it becomes a very easy matter to connect the cells directly to the circuit without a series-gap. In that case a single cell, operating on a potential of 300 volts, will have a loss of energy, internally, of very much less than one watt, the exact amount being 300 times 0.001, or about 0.3 watt for normal operation.

The other type of protector is illustrated in the paper, and consists of a number of cells connected in series and directly connected to the line, using alternating current. That corresponds to the direct-current arrester just described. In this case it is necessary to give a great deal more area of radiation in order to get rid of the extra amount of heat which is caused by the alternating current, the latter destroying and reforming the film every half cycle, and in that way giving a considerably greater loss of voltage as compared with the direct-current cell. It is also necessary in that case to place across each one of the cells a potential regulator, which is nothing more or less than an auto-transformer. The discharge rate of these cells at double voltage, is somewhere between 200 and 400 amperes, and can be measured by an ordinary ammeter, the cells being able to carry the current during that period. The discharge current at normal voltage is a fraction, say about 0.2 of an ampere.

Ralph D. Mershon: What is the voltage to which each cell is continuously subjected ?

E. E. F. Creighton: 220 volts in the latter case.

Ralph D. Mershon: What would be the magnitude of the loss in a case like that?

E. E. F. Creighton: It would be a few watts per cell.

Ralph D. Mershon: Are the cells quite small?

E. E. F. Creighton: Yes; fairly small, about a quart size.

Ralph D. Mershon: What area of plate would that correspond to?

E. E. F. Creighton: That varies in the different cases where we made our tests. We have used large plates and small plates, and it all depends upon the general design. By giving more cooling area a larger plate may be used. Of course the idea is to use as small a plate as one consistently can and have the protection.

Ralph D. Mershon: Is there not some relation between the size of the plate and the amount of discharge the arrester will take care of?

E. E. F. Creighton: Yes, there is a direct proportion. For instance, the larger the plate area the more discharge is obtained at double potential, which really gives the capacity of the surge protector expressed in kilowatts, in the same way as with a transformer. The service the surge protector will be called upon to give is one of the objects we had in making these tests.

Ralph D. Mershon: What happens when the surge protector is too small?

E. E. F. Creighton: It takes energy from the surge proportional to the abnormal voltage and it must necessarily lower every surge that comes on the system.

Ralph D. Mershon: If your plate is not large enough, what results—does it blow the electrolyte out?

E. E. F. Creighton: We have not found anything of the kind so far. The cells will stand a great abnormal voltage, just how much cannot be stated simply—we have had three or four or five times normal voltage for a brief time on them without causing any trouble. It has to be brief in that case, because the size is small, and the current that flows, due to the abnormal voltage, is power current, and therefore an energy loss.

Ralph D. Mershon: I should think that if a heavy discharge took place there would be enough steam formed to make trouble.

E. E. F. Creighton: The one case given here, where a cell was placed across a regulator and the regulator then grounded, gave a very large rush of current through the cell. The cells were exceedingly luminescent, and it was apparently a case of severe arc over the entire area of the plate, and still no change resulted from it. Of course, in that case the voltage was somewhat limited. Furthermore it was quite possible that the frequency was very high, somewhere in the neighborhood of 20,000 cycles, being the natural frequency of the cable without the regulator in series.

Ralph D. Mershon: Is this regulator across each set of cells a transformer with the taps brought out?

E. E. F. Creighton: It is an auto-transformer.

Ralph D. Mershon: Will not the cells divide the voltage properly?

E. E. F. Creighton: They divide the voltage fairly well, but better results are obtained by using the transformer.

Ralph D. Mershon: Why will not they divide the voltages; because the capacities are not the same?

E. E. F. Creighton: Because slight differences between the cells, and little impurities in the plate cause a difference in the capacity current, or energy current, and consequently a variation in voltage resulting from it.

Ralph D. Mershon: Things other than the density of the electrolyte, size of plate itself, etc.?

E. E. F. Creighton: Yes; each has an effect entirely aside from them.

Ralph D. Mershon: Will you explain the matter of destruction and re-formation of the film?

E. E. F. Creighton: The film seems to consist of two parts: there is a skeleton part that requires a long time in forming and seems to be very little affected. Then, apparently, inside of that skeleton, is formed a gas or a liquid of some kind that can be dissolved out. This is dissolved out in every case of every electrolyte that we know of at the present time.

Ralph D. Mershon: That is, if you let the cells stand?

E. E. F. Creighton: Yes, if the cells stand without any current. That same dissolution takes place if the current is reversed, or something similar to that dissolution takes place. That is what causes a loss of energy, we presume, in a cell when the alternating current passes through it; whereas the loss of energy is only a fraction of a watt on direct current, it is several watts on alternating current.

Ralph D. Mershon: On the alternating current, though, is there enough change to alter the color of the film?

E. E. F. Creighton: Yes; this skeleton, when the cells are first formed, has an iridescent color on the outside of the plates. After the cells have operated for a long time, the skeleton becomes thicker, although the film, apparently, does not change; that is, the film thickness is of about the same capacity as before. As it ages it becomes frosty in appearance.

Ralph D. Mershon: What means do you have for cooling?

E. E. F. Creighton: That is obtained by immersion in oil.

Ralph D. Mershon: By the immersion of the cell itself?

E. E. F. Creighton: By the immersion of the cell itself, in the case of the gap aluminum arresters, where a stack of cones is immersed in a tank of oil. In the case of the surge protector, which is the aluminum arrester without the gap, each separate cell is immersed in a horizontal tank or trough of oil.

Ralph D. Mershon: Can you get enough convection in the oil to keep it cool?

E. E. F. Creighton: Yes.

Ralph D. Mershon: In the case of the arrester with a gap in series, is the gap closed at intervals to keep the arrester in operative condition?

E. E. F. Creighton: The normal method is to have a switching arrangement. The gap itself is a switch which can be closed, but it seems that once a day is the best time to do it. It may stand for a long time, especially in cold weather, but charging it every day keeps down that first initial rush of current which must invariably take place in every aluminum cell. Each day that it stands the dissolution increases, and the initial current rush is greater; so if it stands for some time the initial current rush may easily be as great as 300 amperes. That will vary somewhat with the nature of the electrolyte.

Ralph D. Mershon: How many cycles does it take for the film to get back into proper condition?

E. E. F. Creighton: The oscillograms show that it requires just a few cycles for the film to re-form. It is only a momentary rush, which might be compared to the rush in the transformer when it is first thrown on the circuit, it unbalances magnetic conditions.

Ralph D. Mershon: Is that found in the case of a perfectly new cell, or in the case of a cell which has been formed once?

E. E. F. Creighton: In every case, where it has stood in the electrolyte.

Ralph D. Mershon: Whether it has had current or not?

E. E. F. Creighton: Whether it has had current or not, if it has stood any length of time.

Ralph D. Mershon: If you put the raw plates in the electrolyte?

E. E. F. Creighton: I misunderstood your question. It is usually impossible in that case to form the plates. They must go through a preliminary process before that is possible.

Ralph D. Mershon: As to the forming process, and the electrolyte, is that a secret at the present time?

E. E. F. Creighton: Yes; at the present time; these things are still in the patent department.

Charles P. Steinmetz: I think I can answer the remaining question, as to the destruction and re-formation of the film. The oscillograms taken of the voltage and current of the aluminum cell in good operating condition show that at the reversal of electromotive force a slight re-forming of the film is necessary.

An extensive investigation of the operation of the aluminum cell, under normal and under abnormal conditions, on alternating voltages and oscillating discharges, has been made in my laboratory by my assistant Mr. J. L. R. Hayden, by means of the oscillograph. As the interest shown in the subject by the discussion seems to warrant it, we shall present the results in a paper before the Institute at an early date.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 29, 1909.

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THE APPLICATION OF STORAGE BATTERIES TO THE REGULATION OF THE ALTERNATING-CURRENT LOAD AT THE PLANT OF THE INDIANA STEEL COMPANY, GARY, INDIANA

BY J. LESTER WOODBRIDGE

Inasmuch as the paper presented by B. R. Shover before the Institute at the meeting in New York on March 12, 1909, gave a general description of the power plant at Gary, including a brief outline of the storage-battery and regulating apparatus, and the paper presented by the writer at the twenty-fifth annual convention of the Institute in 1908, set forth the general theory of the operation of this storage-battery regulating apparatus, it has seemed advisable in this paper, after a brief description of the battery plant and accessories, to dwell more particularly upon a few of the features which have not as yet been fully described, and then to give an account of the actual commercial operation.

The battery proper consists of two series of cells, each series comprising 125 cells. Each cell contains 73 plates measuring 18⅝ in. by 18⅝ in. The capacity of each cell is 4320 amperes at the hour rate, or 8640 amperes at the usual regulating rate. It will be understood of course that this latter rate is more or less arbitrary, and the cells are capable of discharging momentarily at much higher rates under emergency conditions if the service should require. The two series, operating in parallel, are therefore designed to give a momentary output of 17,280 amperes at double the 1-hr. rate at a voltage which may vary from 225 down to 200, depending upon the duration of the discharge, the state of the battery, etc. Discharges as high as 25,000 amperes have already been taken from the battery.

The batteries are installed in a two-story building, one series of cells being located on each floor. Each battery room measures 46 ft. 3.5 in. by 80 ft. 1.5 in. inside. A view of the upper floor is shown in Fig. 1. Ventilation of the battery rooms is provided by forced circulation of air, the air being taken from outside the building and filtered through wet coke to remove all dirt and particles of iron and then forced into the battery rooms under pressure by means of a centrifugal blower.

In order to provide for the automatic transfer of energy in either direction between the battery and the alternating-current circuit, two split-pole converters have been installed, each having a continuous rating of 6800 amperes, direct current, in either direction with a voltage range from 225 to 275 at the direct-current brushes The momentary overload ratings are for 10,000 amperes output as a true converter at 300 volts, or 14,000 amperes input as an inverted converter at 200 volts, the alternating voltage at the collector rings remaining constant throughout these ranges of direct voltage. The converters are six-phase machines arranged for double-delta connection to the secondaries

FIG. 1.—Battery room second floor diagonal view, Indiana Steel Co., Gary, Ind.

of the static transformers. Only one of these converters was included in the original installation, the second having been ordered soon after the first was completed and tested. One of these machines is illustrated in Fig. 2.

The direct-current terminals of these converters are connected directly across the battery without the interposition of any booster, and the variation of direct voltage required to cause the battery to charge and discharge is brought about by varying the distribution of field flux over the pole face. The general theory of the operation of this type of machine was discussed quite fully at the last annual convention of this Institute, and it is therefore unnecessary to take it up at length in this paper.

FIG. 2

The converters for the Gary installation were originally designed to operate as three-part-pole machines, each pole being divided into three sections, each section being provided with separate shunt-field windings. In this type of machine, in order to reduce the direct voltage without changing the alternating voltage, the field strength of the outer sections of each pole is reduced while the field strength of the middle section is increased, this change in the distribution of the field flux producing a variation in the voltage ratio of conversion. While the first Gary converter was being built along these lines, the two-part-pole converter was developed. The results of a number of tests on the latter type of machine indicated certain advantages over the three-part-pole type, and finally led to a change in the original plan. It was decided to operate the Gary converter as a two-part-pole machine, two of the pole sections being combined and excited as one, with constant excitation, this constituting the main pole, the third section being used as an auxiliary or regulating section, its excitation being controlled automatically to produce the desired variation of direct voltage. The second machine, being designed to operate in parallel with the first, was made identical with it throughout. The excitation for the two main-pole sections is obtained from the 250-volt exciter bus-bar while the winding on the auxiliary-pole section receives current from a specially designed synchronous exciter.

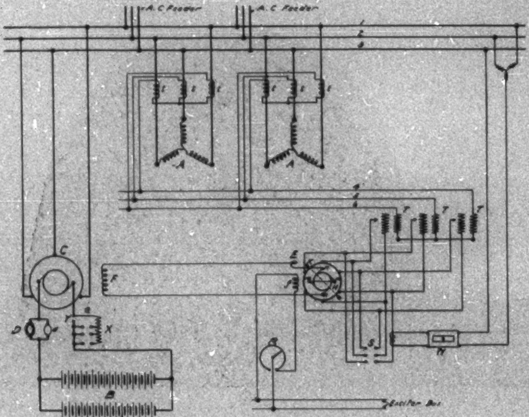

FIG. 3

The theory of this exciter was given in the paper presented by the writer at the 25th annual convention of the Institute in 1908, but it may be well to present a brief review of this theory here. In Fig. 3, which is a simplified diagram of connections of the alternating-current regulating apparatus at Gary, this exciter is shown at *E*. The armature *H* is provided with six collector rings connected to its winding at equidistant points. These collector rings are connected to three current transformers in the alternating-current circuit whose load is to be regulated. The alternating currents thus transmitted through the armature winding will set up a revolving field proportional to these currents. A synchronous motor connected to the alternating-current circuit revolves the armature in a direction opposite to that of the field rotation, thus holding this field stationary in space. The machines are so designed that at unity power-factor this field will take the direction indicated by the arrow *K*. To the armature winding is connected a commutator upon which bear two pairs of brushes. One pair of brushes, *m m* called the auxiliary brushes, is located at points of maximum potential difference due to the field *K*. The other pair of brushes, *n n*, is connected to the regulating field coil *F* of the split-pole converter.

The fields of the exciter are provided with two field windings. One of these is a shunt winding energized from the exciter bus-bars and controlled by the rheostat *R*. The current in this field winding may be adjusted to neutralize the field *K* set up by the alternating current at some particular load on the alternating-current circuit. Under these conditions there will be no potential across the brushes *m m* and they may be short-circuited, as shown in the diagram. This being done, any change in the alternating-current load above or below the value for which the shunt field of the exciter has been adjusted will produce a difference of potential between the brushes *m m*. A small change in the alternating-current load will be sufficient to cause a very considerable flow of current through the short-circuit connection between these brushes, and this flow of current will set up a second field at right angles to the field *K* and of considerable magnitude. This second field produces a potential across the brushes *n n*, and a corresponding flow of current in the regulating field *F*.

If the alternating-current load has increased, the direction of flow of current in the field coil *F* will be such as to cause the battery to discharge, while if the alternating-current load has decreased, the current in *F* will be in the opposite direction, causing the battery to charge. The second field winding on the exciter is connected in series with the field coil *F* and serves to neutralize the armature reaction due to the current output from the brushes *n n*, and thus makes the machine more sensitive. If the power-factor is not unity the alternating current transmitted from the current transformers through the armature winding may be divided into two components; one of these, the energy component, will produce the field K, while the other, being at right angles to this, will pass directly through the short-circuit between the brushes $m\ m$ and have no appreciable effect on the regulation. It will be seen, therefore, that this machine is responsive to the energy component of the alternating current.

In the Gary installation this exciter is an eight-pole machine, the armature being provided with a four-pole winding, and is driven by a four-pole synchronous motor. There are eight brushes bearing upon the commutator, four of these being the auxiliary brushes, which are short-circuited, while the other four are connected in pairs and constitute the main terminals of the machine. This exciter set is shown in Fig. 4.

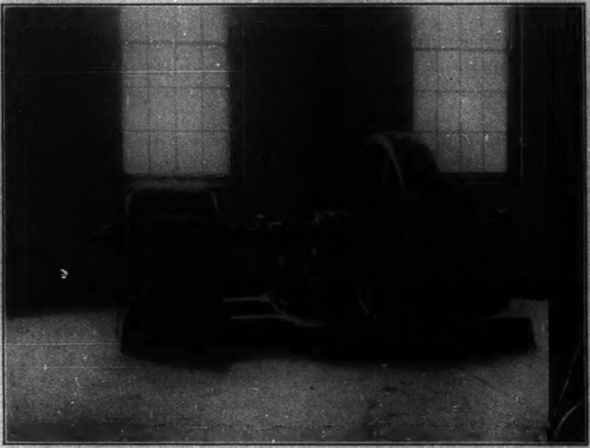

Fig. 4.—Converter auxiliary field exciter, Indiana Steel Co., Gary, Ind.

For supplying alternating current to the exciter, a current transformer is connected into each phase of each of the main generators. These current transformers are connected to a set of common totalizing bus-bars, which in turn are connected to the primaries of three totalizing current transformers. The secondary windings of the latter are connected to the collector rings of the exciter. This arrangement was made necessary owing to the fact that there is no point in the main alternating-current bus-bars of the station through which the entire output of the plant passes, the outgoing alternating-current feeders being connected at various intermediate points between the points of connection of the main generators so that there is no point in the bus-bars where a single set of current transformers could be connected for regulating the total load.

Inasmuch as the main bus-bars of the station are installed in duplicate, it was found necessary to duplicate the totalizing bus-bars for the current transformers. The switching arrangements are such that any number of the main generators may be connected to one set of bus-bars, while others may be connected to the other set. The feeders may also be divided between the two sets. The split-pole converter may be connected to either set of bus-bars for regulating. The oil switches which connect the generators and the converters to the bus-bars are installed in duplicate, one set for each set of bus-bars. The oil switches are provided with pallet switches interlocked in such a way that when the converter is connected to one set of main bus-bars the totalizing current transformers are connected to the corresponding totalizing current-transformer bus-bars. When any generator is connected to either set of bus-bars its current transformers are connected to the corresponding totalizing current-transformer bus-bars. The exciter therefore responds to the fluctuations of load on only those generators which are connected to the bus-bars to which the split-pole converter is connected. The totalizing current transformer bus-bars which are not in use for regulating at any time are automatically short-circuited.

One special feature of the regulating apparatus in this installation is the short-circuiting switch across the secondaries of the totalizing current transformers. When this switch is closed all the current transformers are short-circuited through the totalizing current transformers, and at the same time the exciter is short-circuited on the alternating-current side. This reduces the exciter direct voltage to zero and instantly kills the regulation, but owing to the high armature reaction of the exciter only a small flow of current is set up through the short-circuit switch. In fact, at times when the total load on the plant is just equal to the average load which is being maintained on the generators, so that the battery is neither charging nor discharging, the exciter voltage will be zero under normal operating conditions. The short-circuit switch may therefore be closed without producing any effect whatever. Any variation of load from this point will produce a flow of current through the short-circuit switch proportional to the increase or decrease of load, but will not affect the voltage of the exciter. In one of the leads to this short-circuit switch is connected the current coil of a wattmeter, its voltage coil being suitably connected to indicate the energy component of the current passing through the short-circuiting switch. This wattmeter provides a means for adjusting the shunt field of the exciter to any predetermined average load on the generators before opening the short-circuiting switch. In this way the process of putting the regulating apparatus into service is much simplified.

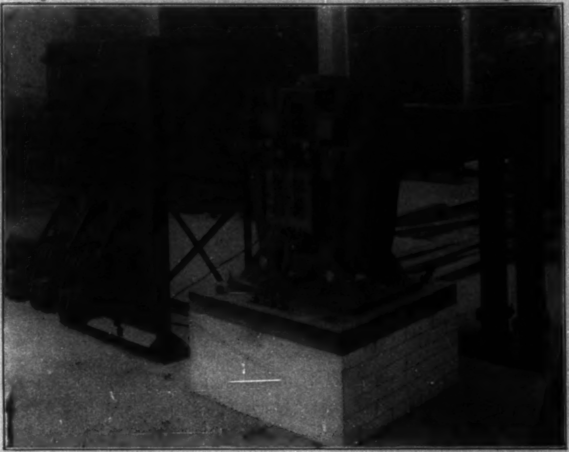

Fig. 5

Fig. 3, as already stated, shows a simplified diagram of connections which will serve to explain more clearly the operation of this regulating apparatus. In order to avoid confusion, most of the switches, circuit-breakers, and duplicate bus-bars have been omitted from this diagram. Two of the main alternators *A A* are shown connected to the main alternating-current bus-bars 1, 2, 3. The static transformers and oil switches which are interposed between the generators and the bus-bars are omitted. Current transformers, *t*, are shown in the generator leads connected to the totalizing bus-bars 4, 5, 6, which in turn lead to the primary windings of the totalizing current transformers *T*. The secondary windings of the latter transformers are connected to the exciter *E*. It will be observed that the ratio of transformation of the totalizing transformers may be varied by cutting in or out coils in their secondary windings.

Fig. 6.—Booster and exciter, Indiana Steel Co., Gary, Ind.

This is shown conventionally on the diagram and is accomplished actually by three dial switches connected to a common shaft and operated by a single hand-wheel on the bench-board.

The short-circuiting switch is shown at *S* and the wattmeter connected to one phase of the short-circuit connection is shown at *W*. The rheostat *R* controls the field *f* of the exciter. The main brushes of the exciter are connected to the regulating field *F* of the converter *C*. This converter is shown connected on the alternating-current side to the main alternating-current bus-bars 1, 2, 3 and on the direct-current side to the battery *B*. The alternating-current connections of this converter are shown three-phase conventionally, the static transformers and oil-switches being omitted. Actually this is a six-phase machine with double-delta connections to the secondary windings of the static transformers. The multiple-contact resistance for starting the converter from the battery is shown at X, the final contact at Y being that illustrated in Fig. 5. The two circuit-breakers, D, and d, are connected in parallel between the battery and the converter, the one of small capacity being used in starting, the other for normal operation.

The method of putting this apparatus into service is comparatively simple. The converter is started by closing its main field circuit and supplying current to its armature from the battery through the automatic starting resistance X and the circuit-breaker d. The machine is then synchronized with the alternating-current bus-bars and the oil-switch is closed. The closing of this switch automatically trips the starting circuit-breaker, d, cutting the converter free from the battery. The direct voltage of the converter is then adjusted by its main field rheostat and the running circuit-breaker D is closed. The

FIG. 7.—Front booster and converter panel (positive side), Indiana Steel Co., Gary, Ind.

battery and converter are then floating on the alternating-current bus-bars. The exciter E is then started up and connected to the field F of the converter, the switch S being closed so that no

FIG. 8.—Battery switchboard, negative side, Indiana Steel Co., Gary, Ind.

voltage is developed in the exciter. The rheostat R is now adjusted until the wattmeter W reads zero. If there is a fluctuating load on the alternators the wattmeter needle will be swinging on either side of zero, but the adjustment may be made so that when the load on the alternators is at the desired average value, the wattmeter *W* will read zero. When this adjustment is effected the switch *S* may be opened and the regulating apparatus will be in operation.

The battery is also arranged to control fluctuations of load on the direct-current bus-bars, to which it is connected by means of two direct-current boosters which may be operated either singly or in parallel. These boosters are provided with carbon-regulator control in the usual manner, the carbon regulator being actuated by a soft-iron horse-shoe magnet suspended over a portion of the direct-current bus-bar. The operation of these boosters in conjunction with the battery is like any other direct-current regulating plant and need not be further described here. One of the boosters with its exciter is shown in Fig. 6.

FIG. 9.—Bench-board Indiana Steel Co., Gary, Ind.

The main switchboard for this regulating apparatus is located on the ground floor of the power house and is shown in Fig. 7. With the exception of the second panel from the left, which contains switching apparatus for one of the direct-current generators, the apparatus shown on this switchboard is employed for controlling the batteries, split-pole converters, direct-current boosters and exciters. All the operating switches are of the remote-control type and are operated from the bench-board in the gallery overhead.

A single 25,000-ampere, remote-control circuit-breaker is interposed between the negative bus-bar and the two series of batteries. This circuit-breaker, with the two battery wattmeters, is shown in Fig. 8. The wattmeters are of the double-dial type registering the input and the output of each series of cells separately. The bench-board, from which all of the switches and controlling apparatus are operated, is shown in Fig. 9.

The results of operation of the battery and converter and the regulation obtained on the alternating-current circuit are shown in Fig. 10. In this diagram the heavy line represents the total load on the alternators whose load is being regulated, while the light line is the sum of this generator load and the battery output expressed in kilowatts. These curves were plotted from readings taken at 5-sec. intervals. The total alternator load was read on a wattmeter connected into the circuit of the totalizing current transformers and suitably calibrated, while the readings of battery output were taken from the battery ammeter and voltmeter.

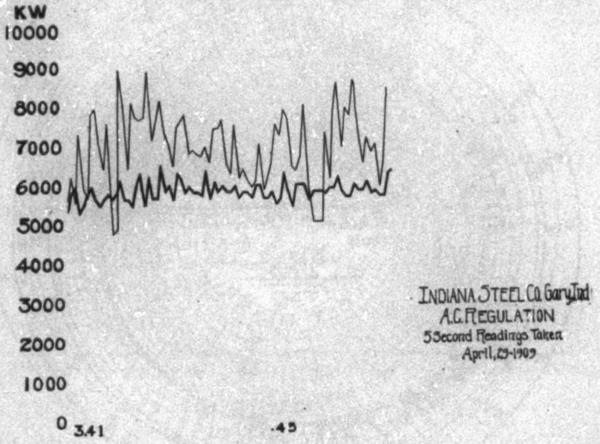

FIG. 10

The effect of the battery regulation on the operation of the entire plant is very marked. In the first place the battery permits the shutting down of one 2000-kw. gas-engine unit, which would be required if the battery were not in service. Even with this additional unit in service, the operation of the plant without the battery involves constant attention by the switchboard attendants and a continual adjustment of generator field rheostats and engine governors. Notwithstanding this constant attention, it is impossible without the battery in service to maintain satisfactory voltage regulation, and the speed of the engines is continually varying over a wide range, whereas with the battery in service the regulation of speed and voltage is all that could be desired.

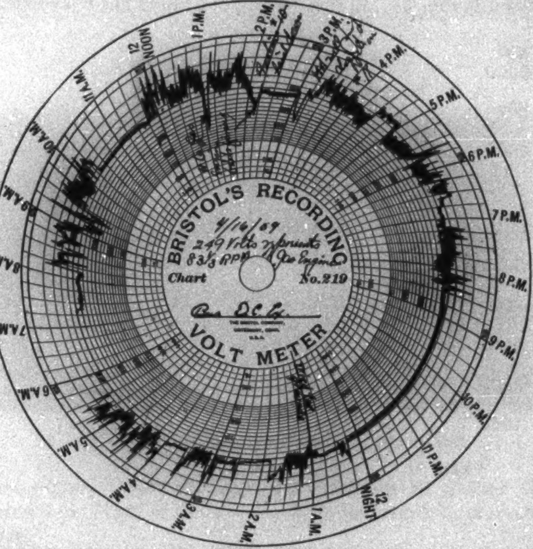

FIG. 11

These effects are clearly shown on the recording voltmeter charts taken from the main exciter bus-bars at the station. Two of these charts are reproduced in Figs. 11 and 12. In explanation of these charts it should be stated that the Gary power house is connected to another gas-engine station in South

Chicago by a three-phase tie-line, so that at times the two power houses are operating in parallel. The chart shown in Fig. 11 was taken with the battery out of service, the tie-line to South Chicago being disconnected. The variations of voltage on the exciter bus-bar as shown on this chart are almost directly proportional to variations of speed of the gas engines, since the exciters are driven by synchronous motors. The chart shown in Fig. 12 was taken with the battery in service. From 7 a.m. to 5.35 p.m. the South Chicago tie-line was disconnected, while during the balance of the 24 hours the Gary plant was operating in parallel with South Chicago. The momentary fluctuation of voltage on the exciter bus-bar occurring at 7 a.m. was due to disconnecting the South Chicago feeder, while a similar fluctuation at 7.30 a.m. was caused by shutting down one gas-engine unit and putting another in service. The severe drop in voltage at 11.15 a.m. was due to the opening of the

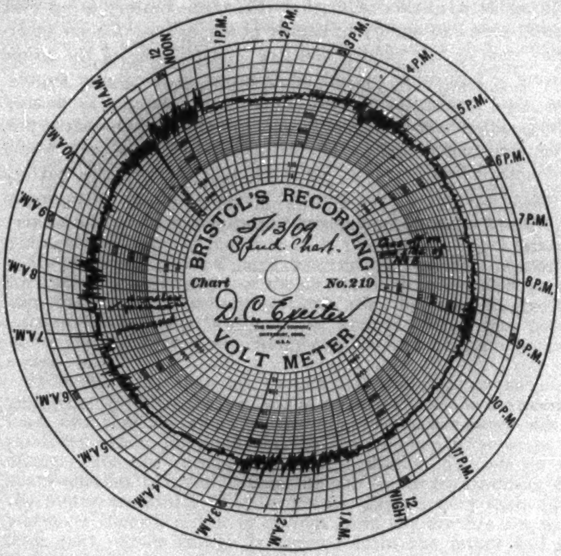

FIG. 12

battery overload circuit-breaker. It should be borne in mind that changes of frequency which are not accompanied by changes of load would not be controlled in any way by the battery regulation and their full effects would appear on these charts

One of the most obvious of the practical commercial results of the battery regulation is the increased speed at which the rolling mill may be operated. When the battery is not in service a very appreciable reduction in the daily output is observed, due to irregularity of speed and voltage.

In addition to this regulating effect, the battery is an ever present source of energy to supply power in case of some emergency such as the sudden shutting down of one of the prime movers or any other partial interruption of the power supply. The vital necessity of continuous power supply to a steel rolling mill is well understood, and the effect of the battery in eliminating costly delays in the operation of the mill would undoubtedly warrant the fixed charges against the battery investment, even if these were not largely offset by the saving in investment for additional generating capacity which the battery replaces.

DISCUSSION ON "THE APPLICATION OF STORAGE BATTERIES TO THE REGULATION OF THE ALTERNATING-CURRENT LOAD AT THE PLANT OF THE INDIANA STEEL COMPANY, GARY, INDIANA." FRONTENAC, N. Y., JUNE 29, 1909

Edward Van Wagenen: As described in the paper, the potential across the regulating brushes *n-n* at unity power-factor is caused by the current from the armature through the auxiliary brushes *m-m*, this current reversing as the energy from the series transformer rises above or falls below the value of the opposing field. At other than unity power-factor the armature will be fed with alternating current, causing a displaced field which may be divided into two components; an energy component desired for regulation, and a so-called non-energy component at right angles to it and therefore causing a potential across the regulating brushes *n-n*. This direct action could easily be made small where plants are designed for coarse regulation, but as the strength of the field energy is multiplied by the factor of regulation, I believe this action would be considerable in plants operating on close regulation such as that required where power is taken from a transmission line or close voltage regulation is required on a plant supplying a variable inductive load. With a plant designed for 5 per cent regulation, for example, the strength of the alternating-current field (energy component) must be twenty times that required to give full current through the brushes *m-m*, and at 70 per cent power-factor the energy and non-energy components are approximately equal.

It seems to me that any variation in potential of the source supplying the opposing field would cause variation in the average load, and that the effect of changing the power-factor will be produced when the load on the driving synchronous motor changes, for the reason that the regulation depends on the space-relation between current in the series transformers and the motor armature. This armature displacement takes place whenever there is a flow of current from the brushes *n-n*, as at least part of the energy is derived from the motor and not entirely from the series transformer, as in the case of the converter used in the previous alternating-current plants operating with true energy regulation.

I think that the above outlined factors would cause considerable deviation from the true energy regulation, thus causing fluctuations on the generating equipment.

J. L. Woodbridge: When I undertook to prepare this paper I expected to have an opportunity to make a good many more tests and observations on the plant at Gary than I have been able to make. The delay in the installation of the second converter, which is only just now being put in service, and the necessity of keeping the first one in commercial operation, have prevented the making of tests which I hope to make later, when there is one spare machine on which I can work.

In regard to Mr. Van Wagenen's point, I think he has failed to distinguish between current out of phase and field out of phase in the exciter. If the power-factor is not unity, there will be a component of current transmitted to the armature at right angles to the energy component, but that component will pass directly through the short-circuit across the auxiliary brushes, and not through the armature winding, inasmuch as the former is a path of very low resistance. That component will not produce a field at all, and consequently will not affect the regulation.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

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FUNCTION OF FLY-WHEELS IN CONNECTION WITH ELECTRICALLY OPERATED ROLLING MILLS

BY H. C. SPECHT

For all kinds of motor drive and particularly for rolling-mill service, where the load conditions are very unstable, the use of a suitable fly-wheel is of great importance. As is well known, the function of a fly-wheel is to take up the sudden shocks and equalize the unsteady loads as much as practicable in order to produce the cheapest installation and obtain the most satisfactory and economical operation. The smallest size of motor and the minimum capacity of the generating plant are obtained when the action of the fly-wheel is such that the load on the motor is constant and equal to the average of all the loads. To a certain extent this will be impossible in rolling mills, and it will be the problem for the engineer to determine the most suitable size of fly-wheel, motor, and generating plant with the auxiliary equipments.

In reviewing the characteristics of the load curve of a fly-wheel in connection with an induction motor, attention is called to Fig. 1, in which the area $A\ B\ C\ D$ represents a peak load, the ordinates giving the torque in pounds at 1 ft. radius on the shaft of the motor or the mill and the abscissas giving the time of rolling in seconds.

Assume that a constant resistance is inserted in the secondary circuit of the motor and that the motor is carrying all the load until the peak is reached. We will then obtain the torque curve $A\ E$, the section below the line $A\ E$ representing the torque developed by the motor and that above $A\ E$ the torque delivered by the fly-wheel. During this time the speed of the motor has decreased somewhat, thus making it possible for the fly-wheel to deliver part of its stored energy to the driven shaft.

At the end of the peak load, the motor begins to speed up, giving energy back to the fly-wheel, as shown by the torque curve *E F*. The energy indicated by the area *E D F* must be equal to the energy indicated by the area *A B C E*, the energy delivered by the fly-wheel.

Since the torque of an induction motor with a constant resistance in the secondary circuit varies almost directly as the slip, an equation for the torque curve *A E F* may be determined as follows:

Let T_1 = the torque at 1 ft. radius developed by the fly-wheel at the start of the peak load.

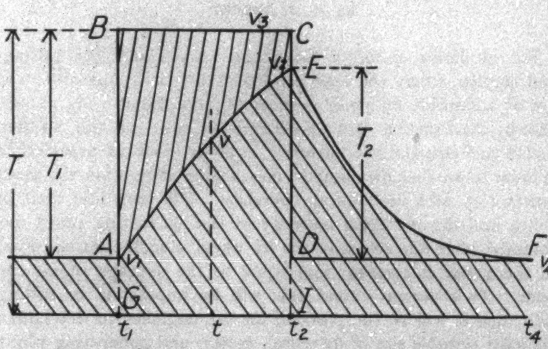


Fig. 1. Showing the relation of the torque of Motor and Flywheel.

T_2 = The accelerative torque developed by the motor at the end of the peak load.

v_1 = the velocity of the motor in feet per second at 1 ft. radius at the start of the peak load.

v_2 = The velocity at the end of the peak load.

v_3 = The velocity if the motor were developing all the torque without the assistance of the fly-wheel.

v_0 = The velocity at synchronism or no-load.

v_4 = The velocity at the beginning of the succeeding peak.

v = The velocity at any time.

t = Time in seconds.

W = Fly-wheel effect; that is, the total weight of the rotating parts multiplied by the square of the radius of gyration.
g = Acceleration due to gravity = 32.2

The equation for the torque curve $A\ E$ during the period of retardation is, then,

$$T_1 - \frac{v_1 - v}{v_1 - v_3}\, T_1 + \frac{W}{g} \cdot \frac{d\,v}{d\,t} = 0$$

or,

$$d\,t = -\frac{W\ (v_1 - v_3)}{T_1\, g} \cdot \frac{d\,v}{v - v_3}$$

integrating,

$$t = -\frac{W\ (v_1 - v_3)}{T_1\, g} \cdot \log \text{nat} \left(\frac{v - v_3}{v_1 - v_3}\right) \tag{1a}$$

or,

$$v = \frac{v_1 - v_3}{e^{\frac{t\, T_1\, g}{W\ (v_1 - v_3)}}} + v_3 \tag{1b}$$

The equation for the torque curve $E\ F$ of the period of acceleration is

$$\frac{v_4 - v}{v_4 - v_2} \cdot T_2 - \frac{W}{g}\ \frac{d\,v}{d\,t} = 0$$

or,

$$d\,t = \frac{W\ (v_4 - v_2)}{T_2\, g} \cdot \frac{d\,v}{v_4 - v}$$

integrating

$$t = -\frac{W\ (v_4 - v_2)}{T_2\, g} \cdot \log \text{nat} \left(\frac{v_4 - v}{v_4 - v_2}\right) \tag{2a}$$

or,

$$v = v_4 - \frac{v_4 - v_2}{e^{\frac{t\, T_2\, g}{W\ (v_4 - v_2)}}} \tag{2b}$$

As examples of the above, Fig. 2 shows several torque curves for different fly-wheel effects and speed-torque characteristics. For simplicity, a continuous cycle of constant peaks of 100,000 lb. has been selected, with half-second periods of duration and half-second intervals.

The fly-wheel effect and the slip for a torque of 100,000 lb. at 1 ft. radius, from which these curves are derived, are as follows:

Curve I—W = 150000, slip at 100000 lb-ft. torque = 10%
" II—W = 300000, slip at 100000 lb-ft. torque = 10%
" III—W = 150000, slip at 100000 lb-ft. torque = 5%
" IV—W = 300000, slip at 100000 lb-ft. torque = 5%
" V—W = 900000, slip at 100000 lb-ft. torque = 10%

It will be noted that curves I and IV are identical; that is, in curve IV, with half the secondary losses or slip and double the fly-wheel effect, the same results are obtained as in curve I with double slip and half the fly-wheel effect. From these curves it can clearly be seen that the greater the fly-wheel effect and the greater the slip for a given torque, the better will be the equalization of loads. When the resistance in the secondary circuit is not kept constant, the foregoing method of determining the torque can be used if the load diagram is divided into sections for which the secondary resistance may be considered constant.

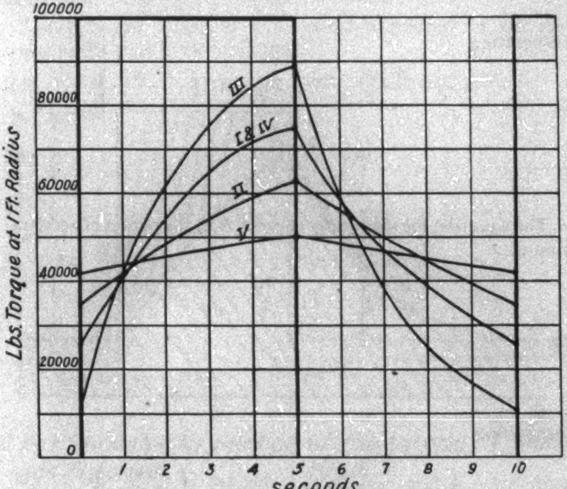


Fig. 2. Showing torque curves for different Flywheel effect and slip

Since the motor must always slow down in speed during the peak loads in order that the fly-wheel may assist it in carrying the load, and since the peaks in all kinds of rolling-mill service vary from pass to pass, it appears that an automatic method of cutting resistance in and out of the secondary circuit of the motor at the proper time would be most desirable. In such a way we could obtain the best equalizing effect and the highest combined efficiency and power-factor.

However, the load conditions in rolling mills are usually such that an automatic control cannot follow the changes of load. For example, in a sheet or a merchant mill where the peaks are quite variable in size as well as in duration and are generally very short, the automatic control cannot be used to advantage. Owing to the time-constant of the automatic controlling devices, the additional resistance may not be inserted at the proper time. This results in the motor at first carrying an excessive load until the resistance in circuit has been increased, when the fly-wheel will assist by delivering part of its stored energy to the shaft. After the peak is over the same sluggishness of the control may prevent the motor from restoring to the fly-wheel all the energy delivered by the latter during the peaks, resulting in a slowing down during succeeding passes. In such a case the automatic control will do more harm than good. Therefore, with such load characteristics the best results would be obtained by having a permanent resistance of the proper amount in the secondary circuit.

In but few rolling mills the periods of peak loads are such that an automatic control can be used to advantage. The duration of all the maximum peak loads must be long enough to allow the controlling devices to act. On the other hand, if the peak loads exceed a certain length of time, an equalization of loads may not be practicable. In this case, the most economical operation would be obtained by running the motor with a small slip and a fly-wheel of sufficient capacity.

In view of the foregoing, it appears that as a general rule for peaks of very short duration (approximately 2 seconds or less), of very long duration (approximately 8 seconds or more), and for extremely variable loads, a permanent resistance in the secondary circuit or a control operated by hand is most desirable. An accurate rule as to the proper kind of control and the size of the fly-wheel can scarcely be given. In each individual case all the possible load conditions should be taken into consideration in order to obtain the best equalization of loads, the highest efficiency, power-factor, etc.

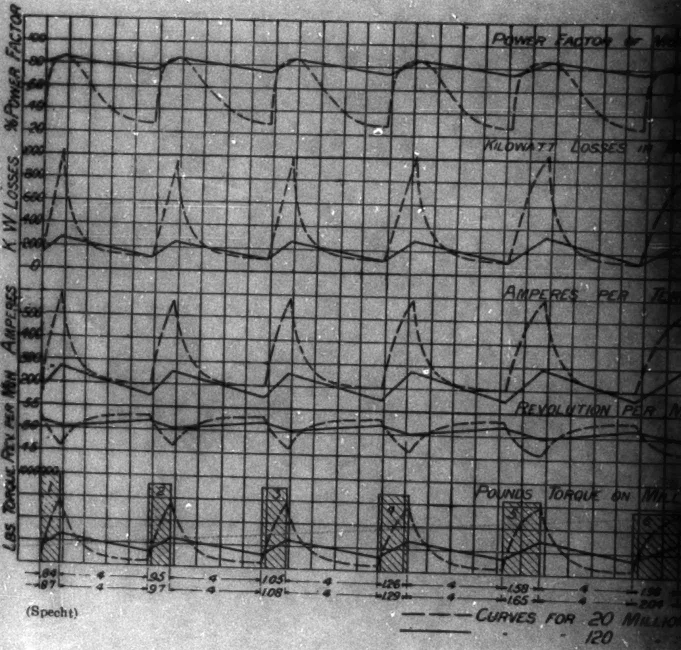
As a rule, the electric manufacturers are forced to submit the lowest-priced outfit with the highest power-factor and efficiency; that is, with secondary directly short-circuited, disregarding the actual working conditions as to the efficiency, power-factor, safety of operation, simplicity of control, etc. What does the efficiency with the secondary directly short-circuited mean to the customer if the motor is not to be run under such conditions?

The cost of operation is dependent upon the combined efficiency of the complete cycle. The highest combined efficiency will require, in most cases, a great fly-wheel effect, and it may be necessary to build a separate fly-wheel in addition to the motor. Considering the fact that the fly-wheel masses of the motor are generally moving at very low velocity and that the fly-wheel effect increases with the square of the velocity or the radius of gyration, it is apparent that a greater fly-wheel effect might be obtained without increasing the weight of the complete outfit by the use of a separate fly-wheel. This might also allow a cheaper and mechanically better construction.

On the other hand, when a very great fly-wheel effect is desired in order to equalize the load, it should also be noted that a greater fly-wheel effect will require more time to stop or start or to change over from one speed to another. Therefore, in a case where this is of great importance, a compromise has to be made between the questions of equalization and time. It should also be borne in mind that the total time of a complete cycle of rolling differs with the different speed controls.

The conclusion from the foregoing is that the cheapest outfit is not always the most desirable, nor does it always give the lowest operating cost. Even if it requires considerable time to work out the best arrangement in all the details, the entailed expenses will be saved many times in the installation and operation. It is somewhat surprising that in the past no more time has been spent in the careful study of the subject, since the future of the electrification of rolling mills depends so much on the first installations.

As an illustration of how to arrive at the most economical result the writer has selected an example with load characteristics similar to those of a universal plate or rail mill. For the sake of simplicity the example has been limited to the first nine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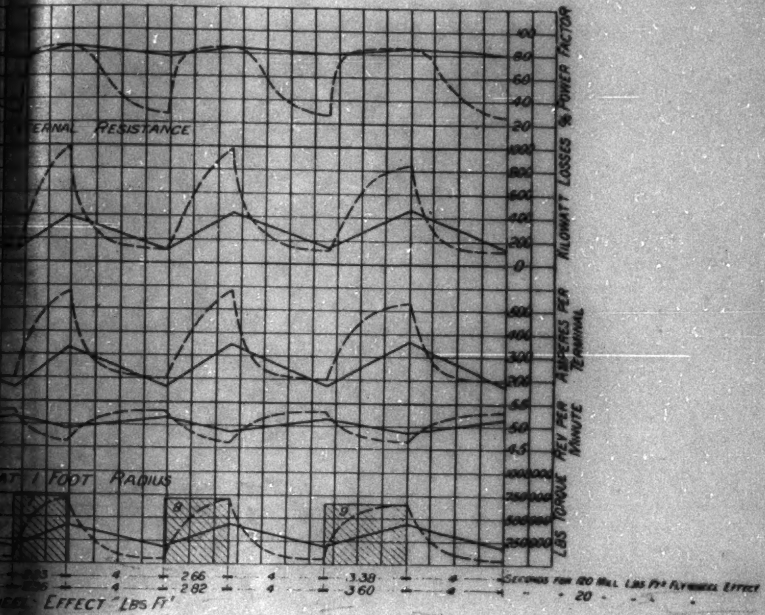
ERNAL RESISTANCE
AT 1 FOOT RADIUS
8
9
100
80
60
40
20
% POWER FACTOR
1000
800
600
400
200
0
KILOWATT LOSSES
500
400
300
200
AMPERES PER TERMINAL
60
55
50
45
REV PER MINUTE
1000000
750000
500000
250000
LBS TORQUE
283
4
266
4
3.38
4
SECONDS FOR 120 MILL LBS FT² FLYWHEEL EFFECT
236
4
282
4
360
4
20
EEL EFFECT "LBS FT"

passes and to two different fly-wheel effects. The data given for this example are as follows:

Pass	Pounds torque at 1 ft. radius	Time in seconds
1	1,000,000	0.82
2	900,000	0.93
3	880,000	1.03
4	840,000	1.24
5	800,000	1.55
6	700,000	1.85
7	720,000	2.17
8	700,000	2.58
9	650,000	3.3

The intervals between passes are four seconds each. The speed is 52 rev. per min. and the supply circuit three-phase, at 6600 volts and 25 cycles. The motor for this speed would, therefore, have 56 poles, which would correspond to a synchronous speed of 53.6 rev. per min. With these data the calculation was made as follows: the average torque and the horse-power for the given load diagram were found to be 261,000 lb-ft. and 2640 h.p., respectively. In arriving at an approximate size for the motor required if the equalizing of loads by the fly-wheel is to be small, the square root of the mean square of the loads is calculated, the torque being 418,000 lb-ft. and the horse power approximately 4100 for normal rating. The design for this size of motor gave a fly-wheel effect of approximately 20,000,000 lb. at 1 ft. radius.

Since the peak loads are of short duration, a speed control having a constant resistance in the secondary circuit was selected. The size of the resistance was made such that a 1,000,000 lb-ft. torque on the motor shaft would correspond to 20 per cent slip.

On this basis, the torque curves were drawn in Fig. 3 by means of formulas 1*b* and 2*b*. For these torque curves the corresponding values for speed, amperes per terminal, kw. losses, and power-factor were obtained from the curves shown in Fig. 4, and plotted in the dotted lines shown in Fig.3.

These curves show that the fly-wheel is very much too small to give a satisfactory equalization of loads and that a much larger fly-wheel is required. Since the fly-wheel masses of the rotor are moving with a very low velocity—not over 3000 ft. per minute—and since it will be almost impossible to add sufficient weight to the rotor without making rather a poor design, it is desirable to build a separate fly-wheel with much greater fly-wheel effect. One of 120,000,000 lb-ft.² fly-wheel effect was selected. Curves for this value and for a motor with the same slip as the foregoing are shown in Fig. 5 and in full lines in Fig. 3.

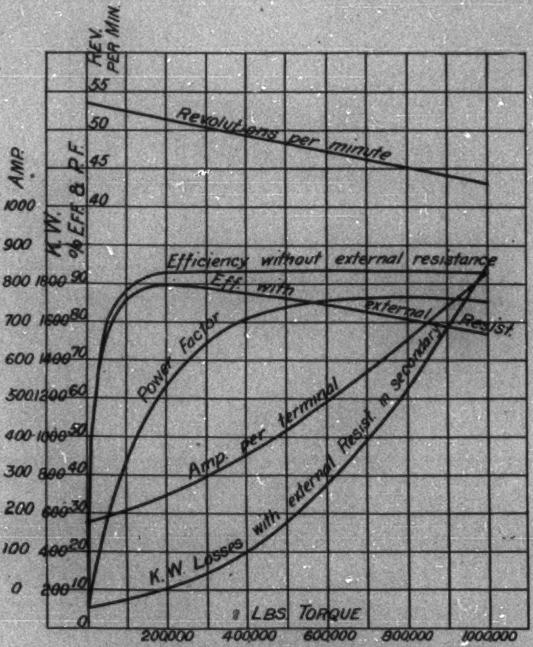

FIG. 4. SHOWING PERFORMANCE CURVES FOR MOTOR WITH 20 MILL. LBS. FT.² FLYWHEEL EFFECT.

Comparing the curves of the smaller and the greater fly-wheel effect shown in Fig. 3, it can easily be seen that the results with the greater fly-wheel effect are very much better in every respect. The power-factor remains nearly constant in comparison with the power-factor for the smaller fly-wheel with which a variation of 28 to 86 per cent occurs during every pass. Comparing further the torques and current values and obtaining from them the square root of the mean squares, we will find

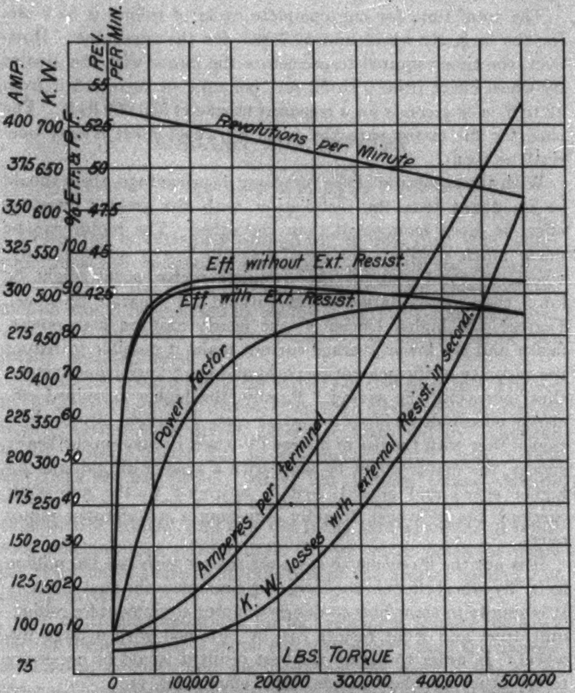

FIG. 5. SHOWING PERFORMANCE CURVES FOR MOTOR WITH 120 MILL. LBS. $FT.^2$ FLYWHEEL EFFECT.

that a motor with a normal rating of approximately 2800 h.p. and a pull-out torque of approximately 700,000 lb-ft. would be large enough, whereas, for the smaller fly-wheel, a motor of normal rating of approximately 3700 h.p. and a pull-out torque of at least 1,200,000 lb-ft. would be required.

Further, by integrating the time losses in Fig. 3 and taking their average value per second, we obtain 212 kw. for the set with the larger fly-wheel and 352 kw. for the set with the smaller. The combined efficiency of the motors, including the losses in the external resistances, would then be equal to 90.3 per cent against 84.6 per cent with the small fly-wheel effect.

The total time for one complete cycle of rolling is 51.9 sec. for the large fly-wheel and 52.7 sec. for the small one. However, the time required to accelerate the motor with the greater fly-wheel effect from 0 to 52 rev. per min. or to retard it from 52 to 0, is 58 seconds for a constant torque of 350,000 lb-ft. The time for the motor with the small fly-wheel effect is only one-sixth of this.

With the exception of the foregoing disadvantage, there should be no doubt that the installation with the greater fly-wheel effect is more economical than the other. The motor can be made much smaller, and even with the heavy additional fly-wheel the total cost for the complete motor outfit might be lower than for the larger motor without the separate fly-wheel. Further, the higher efficiency, the nearly uniform high power-factor and the lower average current make it possible to reduce the capacity of the generating plant and the transmission system, thus increasing the saving. Finally, the higher combined efficiency means also a lower operating cost. It might also be mentioned that with the use of a large fly-wheel to take up the heavy shocks, the motor might be built with a smaller air gap and for higher speed and geared, belted, or roped to the mill shaft carrying the fly-wheel, thereby obtaining a still cheaper motor outfit.

It is not the intention to say that the set with the 120 million lb-ft.^{2} fly-wheel effect in the foregoing example is the final solution. It is simply to show how to design a motor equipment for rolling-mill drive and what results can be obtained with a large fly-wheel. In order to obtain the best result it would be necessary to try other fly-wheel effects, slips, efficiencies, etc.

If rolling-mill propositions are treated in a manner similar to the above, and further, if advantage is taken of more reliable test data, which may be obtained from installations both here and abroad, there can scarcely be any doubt that the electric drive in rolling mills will be a success.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

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ROLLING MILL MOTORS

BY E. W. YEARSLEY

Protection is extremely important in the steel mill where conditions are necessarily uncleanly, and electrical apparatus must work in the midst of dust, moisture, and gases. Large motors should be enclosed in solidly built tight compartments, ventilated by clean air if necessary, or should be of the totally enclosed type.

Considered economically, the writer believes main motor drives to be superior to engine drives, even when power must be derived from a steam-engine-driven generator plant fed by coal-fired boilers. Steam losses due to condensation and leaky valves and rings are surprisingly large, but usually escape definite measurement. Then in the usual rolling-mill engine very little expansion is utilized, and it is not likely that attempts to refine such machines are satisfactory. Where water power or waste gas is available there is no question of the greater economy of electric drive.

The controlling apparatus for mill service is usually the weak part of the system; it is much less satisfactory than the motors. Mechanical strength and simplicity are the main points to be observed in designing this apparatus. Heavier and more mechanical switches and circuit-breakers, better protected and more durable rheostats, and more dependable automatic controlling devices requiring less attention, are badly needed. This is a problem more difficult of solution than improvement of the motor, but no less necessary.

For large main-drive motors the advantage of continuous running at constant speed is so great that it would appear advisable to make the design of the mill suit the characteristics of the motor, and avoid the extra expense and complication of devices like the reversing drive. The tendency has been to build a machine and then to couple on a motor somewhere to drive it. This mistake, while not so frequent as formerly, is still made.

There seems to be no great difficulty in designing mills for continuous-running motors. By combining such motors with a suitable fly-wheel, it should be possible to keep the line load sufficiently uniform. This combination has not, in the writer's opinion, received sufficient attention, possibly because of lack of knowledge of power and speed regulations of the rolling operation.

Tests of these characteristics will be comparatively easy on electric mills, so that data will rapidly become available for supplying the system with the proper inertia. In some installations the writer has seen the fly-wheel so badly proportioned as to be detrimental to the operation of the motor. Initial speeds should be carefully selected, especially when the drive is direct; and if possible a considerable speed regulation should be provided, so that the speed may be increased with increase in proficiency of the operators.

The importance of low armature inertia for reversing motors is now well recognized, but designs could be improved by still further reduction in speed. The writer is decidedly against the use of high-speed motors for any kind of mill service, and believes the extra cost of slow-speed machines well warranted.

Electric motors subject to excessive vibration communicated from the gearing and other parts of the machine should be protected by a flexible coupling.

For mill apparatus which must be handled directly, especially for direct-current apparatus, the writer favors a maximum of 250 volts Safety of employes requires that with higher voltages special guards be provided to isolate the apparatus.

Both alternating-current and direct-current apparatus have their advantages for steel-mill installations. Local conditions must determine which is superior. Unless transmissions are too long, the writer favors a direct-current installation, especially if the plant has many machine tools. With an alternating-current system as few direct-current motors as possible should be used.

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ELECTRIC-DRIVEN ROLLING MILLS

BY E. FRIEDLANDER

The first electric-driven steel rolling mill in the United States was installed about four years ago by the Carnegie Steel Company at its Edgar Thomson works. Since then a number of other electric mill drives have been installed and run with entire success, a noteworthy example being found at the steel plant at Gary, Indiana.

The introduction of the electric drive has made it possible to clear up many points in regard to the power required for rolling different shapes of steel, and moreover, the roller, or operator, is able to see at a glance the work done by each pass. The electric roll drive has also taught us how to get the best relation among rotating masses, speed, time, and horse power. It has helped the roll designer to calibrate rolls in such a manner that the power characteristic for all the passes is uniform, thereby avoiding high power peaks, decreasing the size of the prime-mover, and reducing first cost and fuel consumption.

The watt-hour meter warns the roller that bearings or rolls are becoming tight and hot, or that steel is causing excessive friction in the passes, often due to overfilling, cold steel or faulty calibration, thereby guarding against damage to the rolls and bearings. The meter indicates that lower heat, greater elongation, and especially change of profile in different directions, increase the power required at the rolls much more rapidly than do chemical hardness, high tensile strength, or larger draughts. The meter also shows that it is not the higher percentage of carbon in steel which requires more power in rolling but the lower temperatures at which this steel has to be rolled, and also that an increase in width of the steel shape requires more power than a decrease in height. By means of the meter too, it can readily be seen that rolling "squares" and "rounds" takes per square inch displacement much less power than that of shapes with large peripheries and many flanges, as the latter cool off quickly and cause much friction in the rolls.

Tests on rail-mills have shown that the foot-pounds per square inch of displacement gradually increase the nearer the rail is to the finishing pass. A 75-lb. rail required 1100 ft-lb. at the first pass on the first "rougher. On the same stand in the seventh pass it required 3000 ft-lb., in the first pass on the second roughing rolls 4800 ft-lb., in the fifth pass 8150 ft-lb.; 9500 ft-lb. were required for the last or finishing pass. The large increase in foot-pounds is partly due to the greater density and rapid cooling of the steel, especially at the thinner flanges near the finishing pass. For this reason, the flanges are rolled out as late as possible. Whenever required, exact power consumption can be given for each phase of rolling.

The ideal motive power for rolls should drive them slowly when the steel enters and should drive them faster as the piece lengthens. The reciprocating engine will do just the reverse; namely, run very fast without load and slow down as the load increases, finally stopping if the load becomes too great.

The maximum torque of reciprocating engines is fixed by the size of the cylinders and the pressure; it cannot be increased no matter how much steam or gas is available. For this reason most mill engines are made very large and often run with only half load, causing high steam consumption per horse power, their most economical cut-off being at full load.

For this work the characteristics of the electric motor are much better. Even with double its full torque, the efficiency is good and the motor will not stop, but will take more and more current, finally becoming overheated and burning unless properly protected. If desirable, its speed changes from no load to full load can be made small. The current can also be limited to a certain maximum, without stopping the motor. in this manner preventing excessive strains and probably serious breakdowns.

Where high speeds are necessary, motors can be direct connected to rolls, increasing the energy of the rotating parts and at the same time decreasing the size of motor, the power required and the fuel consumption. Heavy reciprocating engines cannot run at such high speeds, and must be connected to the rolls by means of gears, ropes or belts.

To obtain accurate information as to the exact power requirements for rolling steel, indicator diagrams were taken on reciprocating engines doing similar work, but these in many instances were misleading. The work of rolling steel is very changeable and intermittent. Engines often run with light loads, but at short intervals have their valves wide open. This, together with the work done due to the energy of the rotating parts, should be carefully observed. Although it probably is not difficult to get the maximum torque required to decide on the normal capacity of the motor, the above-mentioned points must be considered, together with the length and number of pieces in the rolls, and also time-intervals between passes. To be on the safe side it is advisable to follow standard mill practice and make motors of ample size and strength, in order to stand the severe service and overloads without injury.

In mentioning fly-wheels, the writer had only three high non-reversible mills in mind. As the weight of rotating parts is much greater in large motors than in reciprocating engines, and the energy of the rotating parts increases as the square of the speed, it is obvious that even a small change in speed is of great importance. As tests have shown that rotating masses are sometimes not only of no use but that they often prove a drag on the motor, careful study of this feature has to be made in each case.

While the steel is being rolled, both the motor and the fly-wheel should furnish the power, but as soon as the steel leaves the rolls the motor should accelerate the rotating masses to the same speed before rolling. The time available and the number of revolutions will determine the size of the motor more than anything else.

It has been observed that on blooming and roughing mills, where the pieces are very short and the intervals long, rotating masses supply the largest part of energy during the rolling period and should therefore be large. The reverse takes place at the finishing passes, where pieces are long and follow each other rapidly. Heavy rotating masses would in this case be useless, and would even require larger motors for their quick acceleration.

Where one motor drives roughing and finishing rolls, curves should be plotted showing the number of pieces in the rolls at the same time, the length of passes and intervals, the power required for each pass, etc. With the help of such curves, the best relation between the sizes and speed of the motor and fly-wheel, radius of gyration, and slip of motor can be easily determined.

The total motive power required in a steel plant is changeable and fluctuates continuously, the average in many plants being often below one-fourth of the total horse power installed in motors. The electric-driven rolling mills will, however, demand considerably larger power-stations to take care of the large currents, especially when all the motors happen to be overloaded at one time, as for instance when rolling cold steel. It is very important to find out beforehand how much of this fluctuating load the power house may have to supply, assuming the worst conditions, as the shut-down of the electric power station for even a very short time, will stop the operation of a large number of machines and cause enormous losses. This is the one very objectionable feature of making such a great number of prime movers entirely dependent on one power station, and, therefore, some means should be taken to prevent this disturbance.

With steam engines and boilers the liability of a complete shutdown is not so great, but the delays and annnoyances caused by low steam-pressure are of daily occurrence in many plants. In such cases not only will all the steam-driven prime movers be unable to develop the required power, but also in trying to develop this power, they will use more and more steam, thus making it difficult to raise the steam pressure without increasing the number of boilers, or decreasing for a while the load and consequently the production.

The short, high-peaked current demands should be kept off the power station as much as possible and only the average current be supplied. The least number of units can then be kept running under nearly full load with the most economical fuel consumption and the least wear and tear of moving parts. As before mentioned, the average current consumption in a steel plant is always small in comparison with motor capacity, on account of the intermittent work and large amount of inertia of the rotating parts. By means of storage-batteries or fly-wheel sub-stations the occasional large demands for current can be taken off the station and supplied from these two sources, where it is stored up when the current demand is below the average.

The exchange of current from one motor to another, in connection with electric roll-drives, is often considerable and should not be overlooked.

With regard to the electric reversing mill, it is a fact that soon after its first appearance the use of reversing rolls became more general, especially in England and Germany. In those countries, small quantities of one kind and shape of material are rolled, and the cost of the large number of rolls required and the saving of time in changing rolls are probably the chief reasons for using the reversing mill, where many different sections can be worked with the same rolls. The absence of the heavy and troublesome lifting tables is also a welcome feature, especially when pieces rolled are very long.

The first installation in this country of an electric reversing mill, at the Illinois Steel Company's works at South Chicago, has given entire satisfaction from the start, and has demonstrated that the electric motor is much better adapted for this kind of work than the reciprocating engine. Although the first cost was high, its lower depreciation, better operation and lower cost of maintenance should justify its installation.

In a reversing mill the operator is able to draw steel slowly into the rolls and " speed up " while the piece lengthens, making a great advantage in rolling steel. In order to obtain perfect speed regulation, no use can be made of steam expansion, but admission continues during nearly full stroke. Even then much depends on the skill of the operator, who can subject the engine and the mill to very severe shocks and cause serious breakdowns if he is not careful. Reversing mills are therefore made heavy and strong.

If too much steam is admitted, it is difficult to prevent such large engines from racing without load. It is also wasteful, as both the time of actual rolling and the speed of the rolls are limited, most of the power being consumed in the rapid starting and stopping of the heavy rotating parts, without making any use of their fly-wheel energy.

With the use of electric motors in place of reciprocating engines, the problem of reversing rolls becomes much simpler and better, in regard to manipulation, fuel consumption, and cost of maintenance. Operation of electric-driven reversing mills is nearly automatic; no skilled operator is required and all danger to the motor and the mill is eliminated. The speed of acceleration is prearranged, and no matter how fast the operator moves his levers, the maximum current and the speed are limited.

Reversing is done with the least shocks in rolls and couplings and the danger of overstraining machinery is done away with. It is important to be able to reverse the motor just as rapidly as the engine. Special care should therefore be taken to have a motor-generator that will give large currents with very low excitation, and one that will be quickly magnetized and demagnetized.

It has been observed that only one-fourth of the power required at the reversing-roll motor is the average supplied from the power station. The large current demands are furnished by the motor-generator through the energy of the high-speed fly-wheel, and a considerable amount of current is sometimes sent back into the line.

As for all other mill work where power and speed variation are considerable, the direct-current motor, on account of its load and speed characteristics, is better adapted for driving rolls than the alternating-current motor. For reversible roll drives it is used exclusively.

There is no reason why the direct-current motor should give any more trouble than the direct-current generator at the power station. Four years' experience has shown that the wear of the commutator and the cost of maintenance amount to practically nothing. The transmission of large low-tension currents is much more serious, especially when tens of thousands of horsepower have to be supplied and the distance of the motors from the station is considerable.

The use of higher direct-current voltages in connection with large rolling mill motors should be satisfactory; but no doubt high-tension alternating-current transmission and induction motors direct on the line will be generally employed, especially in new installations. Where conditions demand it, the induction motor characteristics can now be made nearly similar to those of the compound-wound, direct-current motor. However, much of its simplicity and efficiency will be sacrificed in doing this.

Among some of the earlier disadvantages of the induction motor were: very large current required for starting under heavy load; one speed fixed by the number of poles and the tendency always to run at synchronous speed; low power-factor with light loads; small air gaps; impracticability of reversing large units; and inability to change speed to fly-wheel requirements.

In the design of the modern rolling-mill motor, most of these objectionable points have been remedied by different means such as wound rotors, the introduction of variable resistance, changing the number of poles, shifting the phases, slip-rings, etc.

Whether direct-current power stations and direct-current motors are used, or alternating-current stations are installed for high-tension transmission with alternating-current motors directly on the line or fed through transformers, or direct-current motors are supplied from an alternating-current station through converters, or motor-generators, batteries or fly-wheel substations, is a matter of detail. No doubt any one of these systems will give satisfaction if properly designed and installed.

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POWER REQUIREMENTS FOR ROLLING HIGH-CARBON STEEL OF SMALL SECTION

BY BRENT WILEY

The tests* in this paper were taken from a 9-in. merchant mill, a plan of which is shown in Fig. 1. The mill consists of seven stands of three-high rolls and one finishing stand of two-high rolls driven by a two-speed, two-phase, 60-cycle, 2200-volt induction motor of squirrel-cage rotor construction connected to the mill by means of a 42-in. three-ply belt. The ratings of the motor are 600 h. p. at 600 rev. per min. (synchronous speed) and 450 h. p. at 450 rev. per min. The pulley reduction gives a mill-speed of one-half these values.

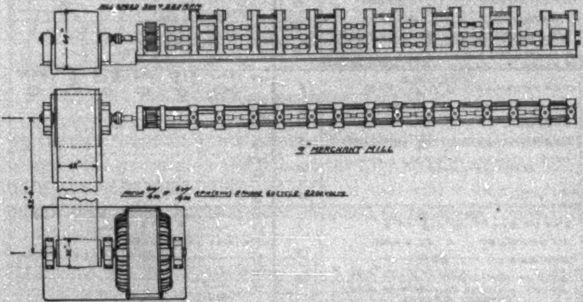

FIG. 1.—General arrangement of mill.

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[*] The tests referred to in this paper were conducted under the supervision of C. J. Russell, through whose kindness they are presented in this form.

	PASSES	STAND NO. 1	2	3	4	5	6	7
TEST NO. 1 SIZE OF BILLET 1¼" X 1¼" X 25'-¾" WT. OF BILLET 11 LBS. CARBON .80 SIZE OF FIN. STOCK 1½" X 16 GAUGE X 45'-0" NOTE:- POSITION OF PIECE IN ROLLS IS INDICATED BY SIGNS- | MEANS PIECE ON EDGE.	1	.155 —	.207 —	.026 |	.033 —	.039 —	.034 —	.021 —
	2	.078 —	.138 —	.035 —				
	3	.053 ◇		.025 |				
	4	.027 ◇						
TEST NO. 2 SIZE OF BILLET 1½" X 1½" X 76" WT. OF BILLET 32 LBS. CARBON 1.20 SIZE OF FIN. STOCK 1" X 3/16" X 47'-0"	1	.1116 ◇	.435 —	.104 |	.0491 |	.051 |	.0492 |	.0416 —
	2	.102 ◇	.283 —	.034 —	.034 —	.0416 —		
	3	.0492 ◇						
	4							
TEST NO. 3 SIZE OF BILLET 1½" X 1½" X 76" WT. OF BILLET 32 LBS. CARBON 1.20 SIZE OF FIN. STOCK 1 3/16" X 7/32" X 34'-6"	1	.335 —	.228 —	.147 |	.0716 |	.1018 |	.0327 |	.0281 —
	2		.168	.1002	.0473	.043		
	3							
TEST NO. 4 SIZE OF BILLET 1½" X 1¼" X 36" WT. OF BILLET 16 LBS. CARBON .90 SIZE OF FIN. STOCK ⅜" ROUND.	1	—	⬭	◇	—	—	⬭	○
	2	⬭	◇	◇				
	3	◇						
	4							
TEST NO. 5 SIZE OF BILLET 2½" X ⅝" X 47" WT. OF BILLET 10¾ LBS. CARBON .80 SIZE OF FIN. STOCK 2" X .041" X 35'-0" * LOAD VERY LIGHT. ϕ STOCK AT BLACK HEAT, LEAVING PASS	1			.073 |	.096 —	.098 —	.0375 —	.0219 — ϕ
	2			.305 —			.0312 —	
	3			.0278 | *				
	4			.0491 —				
TEST NO. 6 SIZE OF BILLET 1¼" X 1¼" X 9'-8" WT. OF BILLET 50 LBS. CARBON .90 SIZE OF FIN. STOCK 5/16" ROUND X 196'-0" NOTE:- STARTED TO THREAD WHEN LEAVING 3rd PASS.	1	.329	.3315 ⬭	[illegible] ◇	.043 ⬭	[illegible] ◇	[illegible] ⬭	[illegible] ○
	2	.473 ⬭						
	3	◇						
	4	.079 ◇						
	5	◇						
TEST NO. 7 SIZE OF BILLET 1¼" X 1¼" X 5'-6" WT. OF BILLET 26.6 LBS. CARBON 1.29 SIZE OF FIN. STOCK 1" X .193" X 36'-0" NOTE:- * THESE TWO PASSES WERE IN SAME GROOVE. ϕ THESE TWO STANDS WERE UNCOUPLED	1	.1057 ◇	.3480 —	.0817 |	.0517 |	.0645 —	ϕ	ϕ
	2	.0745 ◇	.3180 —	.0275 —	.0478 |			
	3	.0203 ◇	.0645 — *					
	4		.1380 |					
	5		.0275 — *					
TEST NO. 8 SIZE OF BILLET 1¼" X 1¼" X 61" WT. OF BILLET 24½ LBS. CARBON .85 SIZE OF FIN. STOCK 13/32" ROUND X 61'-6" NOTE:- WAS THREADED FROM 3rd TO 4th STANDS.	1	—	⬭	◇	—	—	⬭	○
	2	⬭	◇	◇				
	3	◇						
	4							

Table showing data for the eight sets of curves. The decimals show the reduction per pass, and are calculated in terms of the area of the section for the preceding pass. To obtain percentage of reduction multiply decimals by 100.

The product of this mill is high carbon steel of comparatively small section, test data being given for steel ranging from 0.80 to 1.29 carbon and of section ranging from $1\frac{3}{16}$ in. by $\frac{1}{32}$ in. to $\frac{5}{16}$ in. round. Originally the intention was to run the mill on the slow speed for the larger sections and on the high speed for the small rounds and very thin flats, but on testing the high-speed operation it was found that special provisions would have to be made for handling the stock as it was being rolled, including the use of repeaters for the finishing stands. It was also difficult to enter the material in the rolls at the high speed. These plans have not been fully developed and all material is being rolled on the slow speed. The results obtained under these conditions are most gratifying, as a comparison with a steam-engine-driven mill of the same general design but of five stands of rolls shows that the capacity of the latter mill is exceeded by that of the motor-driven mill by 35 per cent. This difference is

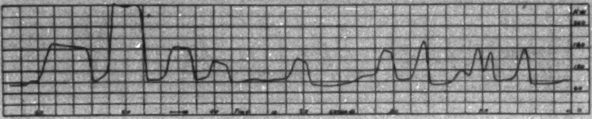

FIG. 2.—One piece in rolls, Test No. 1.

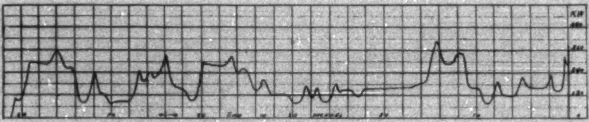

FIG. 3.—Rolling conditions, Test No. 1.

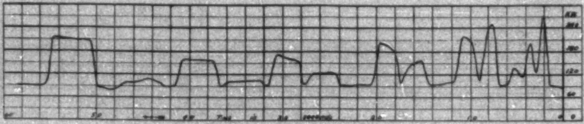

FIG. 4.—One piece in rolls, Test No. 2.

partly due to the two additional stands of rolls, but chiefly to the practically constant speed of the motor, as the average speed of the engine is appreciably reduced by the heavy load conditions.

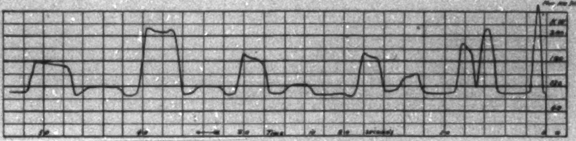

Fig. 5.—One piece in rolls, Test No. 3.

It will be seen that the areas of the sections at each pass are only approximate, but the relative values, which are of more importance, give a good idea of the operating conditions and work done.

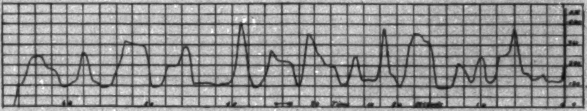

Fig. 6.—Rolling conditions, Test No. 3.

The recorded readings as shown by the series of curves were taken to obtain the power required per pass, the total power for one piece of stock, and the power requirements when the mill was in regular operation with several pieces of stock in the rolls at one time. These latter data were, however, not obtained for tests Nos. 2 and 6.

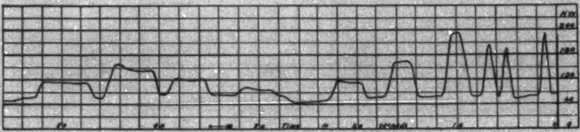

Fig. 7.—One piece in rolls, Test No. 4.

An all-day record was kept during test No. 7. The results give a good idea of the capacity and the average power requirements per ton of product.

Records observed from 6:55 a. m. to 3:49 p. m.

Size of stock rolled..........1 in. by 0.193 in. by 36 ft-0 in.

Carbon..1.29

Size of billet..............1.25 in. by 1.25 in. by 5 ft. 6 in.

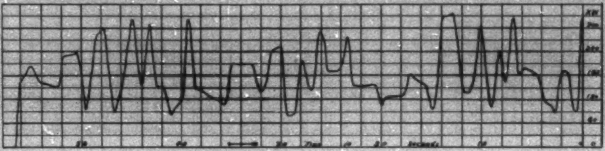

FIG. 8.—Rolling Conditions, Test No. 4.

Weight of billet...............................26.6 lb

Number of billets rolled..........................1121

Total weight of billets.......................29,818 lb.

Actual operating time............................408 min.

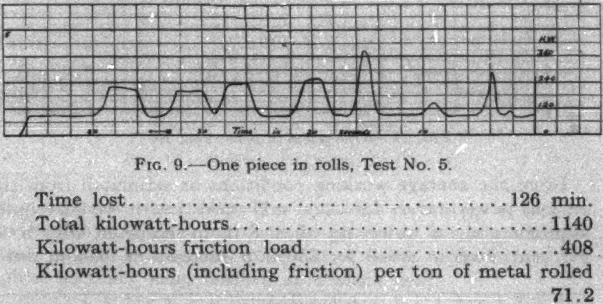

FIG. 9.—One piece in rolls, Test No. 5.

Time lost....................................126 min.

Total kilowatt-hours...............................1140

Kilowatt-hours friction load........................408

Kilowatt-hours (including friction) per ton of metal rolled 71.2

Rate of rolling 22 tons in 12 hr.

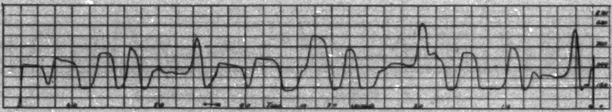

FIG. 10.—Rolling conditions, Test No. 5.

Recorded readings as shown in Figs. 12 and 13 were taken during the above run.

The fly-wheel effect of the system is practically limited to that of the rotor of the motor; this effect is comparatively small, as the slip of the motor is but 3 per cent. at full load. The efficiency of the motor is, therefore, kept as high as possible. By referring to Fig. 6 (test No. 3), it will be seen that the peak-load conditions have a duration of from 4 to 6 sec; to equalize this load to the average power would require an excessively large flywheel on the mill-shaft, and the slip of the motor would have to be increased approximately three times the present value, thereby lowering the efficiency of the motor.

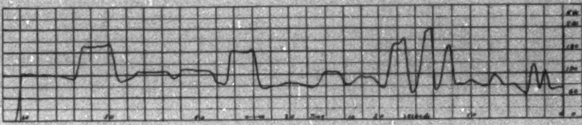

Fig. 11.—One piece in rolls, Test No. 6.

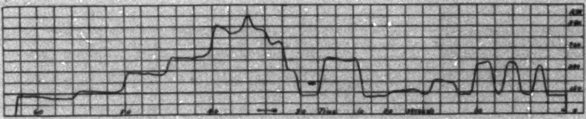

Fig. 12.—One piece in rolls, Test No. 7.

From the average working conditions as estimated from the various power curves for usual mill operation, it would require approximately a 15-ton fly-wheel 8 ft. in diameter, with a 10 per cent. drop in speed for 250 h. p. increase of load in order to lower appreciably the peak values of the load. In this case the fly-wheel is located on the mill-shaft and the peak loads are considered of 4 seconds duration. The time and efficiency costs of this equalization do not warrant the use of a fly-wheel in the system.

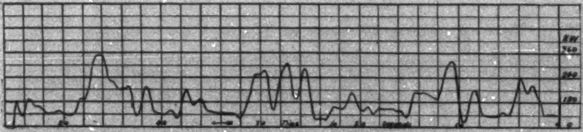

Fig. 13.—Rolling conditions, Test No. 7.

The friction load of the mill is somewhat high, this being due principally to the fact that it is necessary to keep the mill adjusted very closely. Every precaution is taken to keep the mill tight, which results in heavy pressures in the bearings.

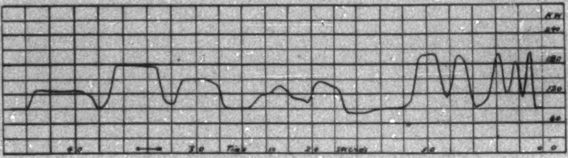

FIG. 14.—One piece in rolls, Test No. 8.

It is generally supposed that, owing to its hardness, more power is required to roll the high-carbon steel than the ordinary mill steel, but at the same temperatures the energy required is practically the same. Owing to the high percentage of carbon, the harder steel billet must not be heated as hot as the milder steel, and it is therefore rolled at a lower temperature, the lighter sections being finished at a black heat.

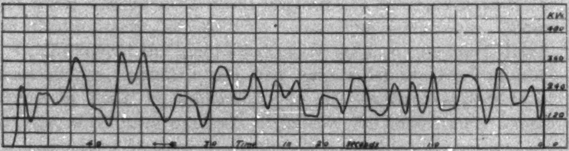

FIG. 15.—Rolling conditions, Test No. 8.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

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ELECTRIC CONTROL FOR ROLLING-MILL MOTORS

BY C. T. HENDERSON

Much has been said regarding the remarkable electrical applications during the last few years in connection with the iron and steel industry, but only those directly interested in this work realize how much impetus has been given to it by the development of suitable controlling apparatus. When A. C. Dinkey, then chief electrician of the Carnegie Steel Homestead works, installed the first electric motor for roll-table service in 1893, he naturally used the standard apparatus of the day, and quite naturally it failed. He immediately sought for something better, especially in controlling apparatus. At that time the only service comparing in severity with that encountered in rolling mills was in electric railway practice; accordingly, the railway motor was rewound for 250 volts and placed in service. In controllers not even temporary satisfaction was found in the devices available, so Mr. Dinkey developed a simple rheostatic controller of the face-plate type. This controller, or one similar to it, together with the rewound railway motor, supplied the demands for about 12 years. Meantime, however, it was found that mill service was much more severe than railway service—more severe in the number of starts and stops per hour, in continuity of service, in lack of intelligent handling, and in the initial temperature of the surrounding atmosphere. It should be said, too, that the penalties of delay in the mill are much higher. If a car in a traction system is put out of service, it can, at the worst, wait and be taken to the car-barn by the following one, without causing essential money loss. But a steel works is unusual in being a manufacturing plant in which there is no reservoir: the material must pass through in an uninterrupted stream; for a delay at any point breaks up the process all along the line, resulting in the derangement of the entire system, much spoiled steel, and consequent loss.

Again a steel plant is unique in the relation of the initial cost of the installation to the value of the product. The Gary plant, with its large and costly electrical equipment, can roll a value in finished product equal to the entire cost of the plant in a couple of months. So it has come to pass that a steel concern figures that the loss of a blooming mill, for instance, in time of good business, costs somewhere between $300 and $1000 per hour, depending upon its capacity.

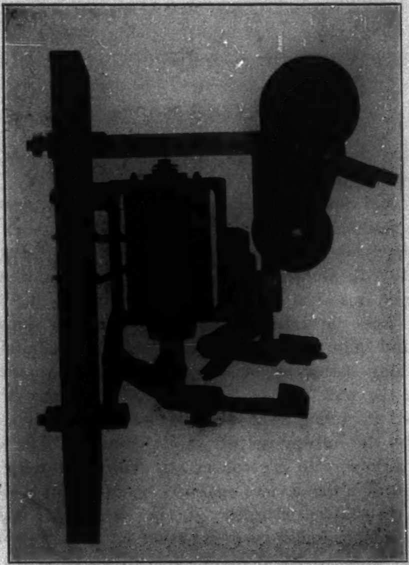

FIG. 1—Contactor type switch

Though in the light of present-day practice the first motors and controllers in steel works were unsuited to the work, they grew steadily in favor, and continued to supplant steam auxiliary apparatus. But as the number of motors increased the dissatisfaction with existing types of controller increased correspondingly. Series-wound motors with a torque almost directly proportional to the current were hardly satisfactory substitutes for steam engines (whose torque was limited by piston area and boiler pressure) when the controllers were operated by ignorant and often vicious persons. To remedy this defect in the operating conditions, about the year 1900 there appeared various devices for properly controlling the motors. Lack of ruggedness caused most of these devices to fail, and it was not until about 1903 that really serviceable apparatus of this nature came into use. From the start the necessity for current-limit control was recognized, and apparatus was designed to make the period of acceleration dependent on the current supply to the motor, the control system being an

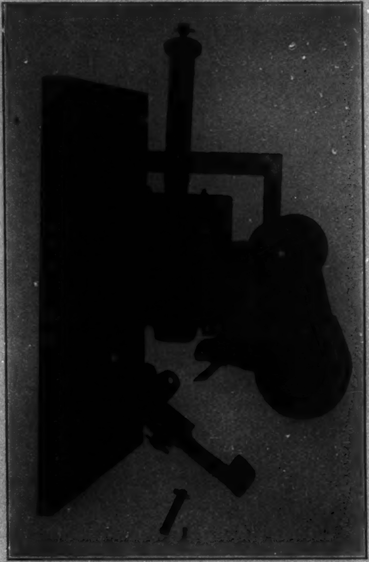

FIG. 2—Contactor type switch opened for repairs

organization of magnetically operated switches whose details left much to be desired on account of the steel mill practice of making repairs on Sunday. At first the demand was for a controller made up of switches rugged enough to operate continuously for 6 days; this was produced late in 1903. Soon there was a demand for a switch more rugged and more susceptible to quick repairs when such were needed.

The importance of minimizing delays in steel mill work has already been touched upon. Apparatus of this nature was produced in due time. Its design may be of interest. Fig. 1 shows a typical switch for this purpose. It consists of a cast-steel frame carrying a fixed contact on an insulated block, and having hinged in it a movable contact lever adapted to be moved by the solenoid plunger into and out of engagement with the fixed contact. The main or current carrying contact is of laminated copper, protected

FIG. 3—Contactor type switch after 60,000 operations

from arcing by auxiliary contacts of carbon and copper normally in the field of a powerful blowout. The poles are shown in Fig. 1, swung up, as they are in practice, to facilitate inspection and repairs. In designing this switch the strength of the materials used was determined by the destructive power of the average repair man. The arrangement of parts is laid out to minimize the probability of delay, should the parts break. For instance, the carbon auxiliary contact is so placed that it will be actuated by gravity should its spring be broken.

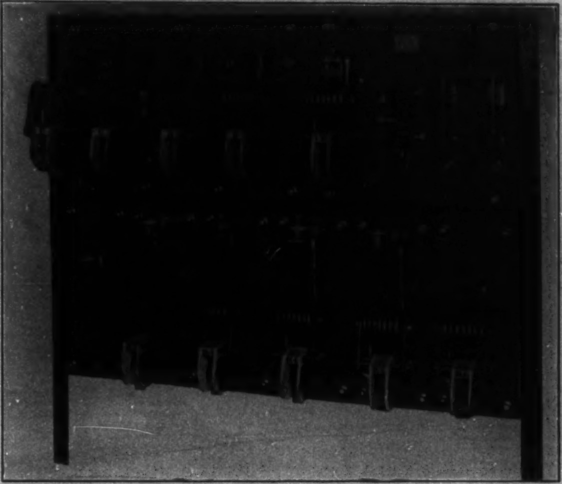

FIG. 4—Contactor type switchboard

Every effort has been made to minimize the time required for replacing defective parts; for example, new arcing contacts can be put in in 15 sec., a new arcing contact spring in 20 sec., a new magnetizing coil in 1 min. 40 sec. (Fig. 2). In case of serious trouble, the switch being self-contained, it can be removed from the board as a unit, replaced by another, and then taken to the shop to be repaired at leisure. This exchange has been made with a delay of 1 min. 30 sec. Numerous experiments and observations seem to indicate that the life of contacts on a switch of this kind varies inversely as the square of the number of operations per minute.

Fig. 3 shows a contactor after opening and closing a high inductive circuit carrying 120 per cent in excess of its normal rating 66,000 times at the rate of 30 operations per min. Both auxiliary contacts have about reached the end of their life, and hence require renewal. Reduced to 10 operations per min., which is about the average rate, this switch should operate about 600,000 times without requiring renewals, and longer under normal load conditions instead of 120 per cent overload. In service this type of switch has operated over 1,000,000 times without repairs.

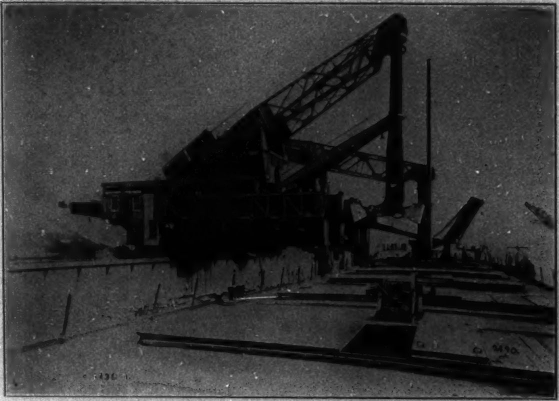

FIG. 5—Hulett unloader

It has been said that the necessity for current-limit control was recognized very early. The first systems employed were far too complicated. Further, they were adapted to maintain the accelerating current at an approximately constant value. In many instances this is undesirable; for instance, where motors are reversed while in rotation, the high armature reaction makes them incapable of commutating current that could be commutated safely when starting from rest. Again, as the motor comes up to speed its commutating limit falls off. This is taken care of in modern controller practice by having a multiplicity of current relays, one associated with each accelerating switch, so that the current can be adjusted independently at each point in the cycle. (Fig. 4.)

Starting at the docks where the ore is unloaded and shipped to various steel plants, we find one of the most spectacular machines in the steel industry, the Hulett unloader. Figs. 5, 6, 7, and 8. These machines were originally steam-hydraulic operated, and have been successfully electrified only during recent years. The operator rides in the bucket-leg and controls all motions of the unloader. The walking-beam carrying the bucket-leg must be started smoothly and quickly when the bucket has been filled, then slowed down and stopped automatically at the top. In lowering, the hoist motor must be transformed into a generator and serve as a retarding means.

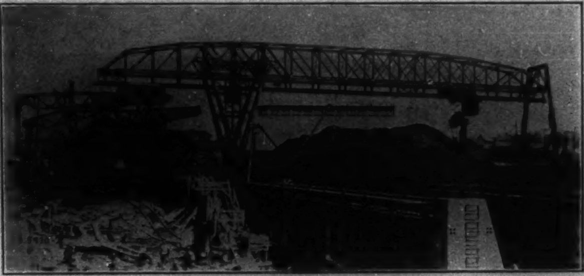

Fig. 6—Hulett unloader

At the bottom, when the operator throws his master controller to the " off " position, the beam must be brought to rest quickly and smoothly. This is accomplished by the same current limiting devices used in acceleration. So perfect are the results obtained, that riding in the bucket-leg reminds one of a trip in a hydraulic elevator.

The bucket, which handles 10 tons per trip, can be rotated so as to pass between hatches, and automatic control of this motion serves to limit the rotation to seven-eighths turn either way from the normal position. The bucket having been rotated 90 degrees, it is easily seen that if it should get caught on a stanchion while closing, the enormous side strains would be thrown on the supporting beam. This distinctly calls for current-limit control of the highest order. Since such apparatus has become available, it is possible to reduce the weight of the machine 15 per cent by reason of the elimination of these extraordinary strains.

During the present season four such machines of 15 tons capacity per trip are being installed. Aside from their huge size they have many interesting features. They are made to span five railroad tracks, and carry a weighing larry that runs across these tracks. The bucket conveys ore from the hold of a vessel into a hopper, from which it is drawn into the larry and weighed. From the larry it is dumped into railroad cars, being weighed by subtraction on especially constructed scales during the process. Thus the cars are loaded and weighed without the necessity of first weighing the empties. Furthermore, each car is loaded to its capacity, a feature of great importance to docks whose daily tonnage is limited by the cars available.

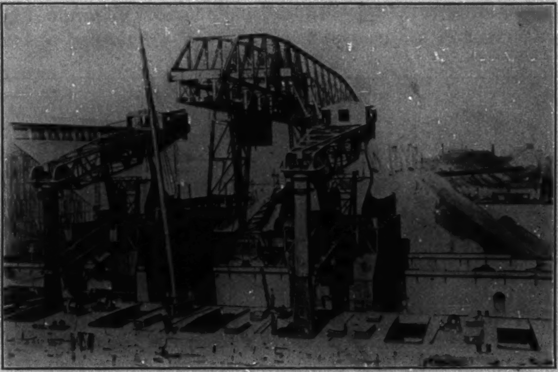

Fig. 7—Hulett unloader

In ore-bridge practice the availability of proper controlling apparatus has brought about a change in design but little short of revolutionary. To-day in grab-bucket hoists in place of the single motor of 15 years ago, we have the double-motor system, in which the drums are driven by individual motors, thus eliminating the friction clutches, and, by making the operator's physical task easier, increasing the capacity of a given plant. These same motors, equipped with current-limiting, dynamic-braking controllers, can be made to act as generators during lowering, thus retarding the downward movement of the bucket, and transforming the kinetic energy stored therein into heat in a rheostat. Here its conversion is not attended by mechanical abrasion, and hence the necessity for continual adjustments is eliminated. During the lowering operation the braking of either of the two motors can be varied independently, and thus the bucket made to open gradually, close gradually, or remain with the jaws at a fixed opening, as desired.

In the steel plants themselves the complete electrification of auxiliary machinery was not attempted until some time after both controlling apparatus and motors had been brought to a condition closely approaching perfection. As late as 1905, steel plants were erected in which all auxiliary machinery (except the blooming-mill tables and elevating mechanism in the case of three-high mills) was electrically operated. Gradually the prejudice against electrically operated blooming-mill tables was overcome, but the elevating-table mechanism seemed destined to remain hydraulic. When the problem presented is considered carefully, the hesitancy on the part of the mill owners must be acknowledged to be justified. The elevating tables referred to consist of live rollers which must be elevated or lowered between passes, first to admit the steel to the lower pair of rolls, then return it to the upper pair. The rolls are very heavy, seldom weighing less than 100,000 lb., and must be operated in

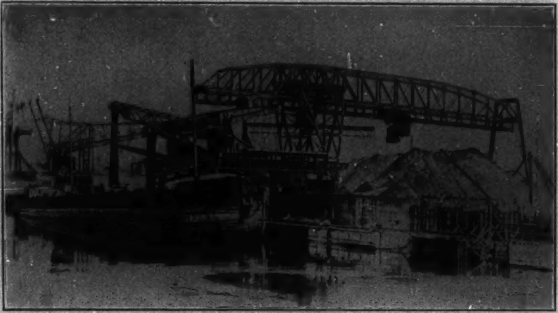

FIG. 8—Hulett unloader

very short periods. At last a steel plant was found which was building a new 40 in. blooming mill; this plant was willing to put in the electrically operated table mechanism, if it could be shown to be feasible. A careful investigation of the speed in other plants showed that the shortest period required by hydraulic equipments to raise or lower was 3 sec. To insure the table being fast enough, the steel company's specifications required a complete cycle in 2.5 sec., apparently on the supposition that the equipment would not come up to specifications, and that by specifying a 2.5 sec. period they would insure operation in 3 sec. This table weighed 118,000 lb. and was required to rise a total distance of 40 in.

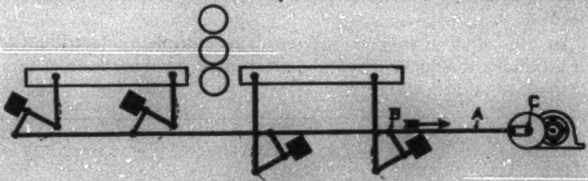

Fig. 9

The arrangement adopted is shown diagramatically in Fig. 9. The motor finally decided upon was 160 h.p. at 88 rev. per min., geared to a crank at a ratio of 1 : 5.8. This crank is connected to four bell-cranks carrying the table. The bell-cranks also carry counterweights aggregating 89,500 lb., giving a total mass of 207,500 lb. to be moved. The ingot to be rolled weighs 10 tons, and the counterweights are so disposed as to counterbalance the table and ingot. Thereafter the problem becomes merely one of starting and stopping, but with enormous masses and unusually short time-periods involved. If the connecting rod *A* were of infinite length, plotting the movement of point *B* in the direction of the arrow against

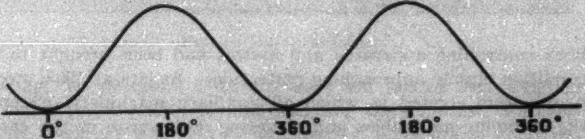

Fig. 10

the degrees of rotation of crank shaft C would result in a true sine curve, Fig. 10. Taking this curve as a basis, it is easily seen that during the first few degrees of rotation there is but little movement imparted to the connecting rod and hence to the table. This being true, almost the entire starting torque of the motor is available for accelerating its own armature; and if it is accelerated before the curve begins to rise abruptly the full torque will then be available for accelerating the table and counterweights. At the top the table is decelerated by virtue of the shape of the curve, the full torque of the motor being again available for retarding its own armature. While the connecting rod used in actual practice is so long as somewhat to distort the rotation-movement curve, Fig. 10, at the same time this curve is close enough to that obtained in practice for an understanding of the installation.

Fig. 11—Three-high blooming mill with motor-operated elevating table

The first installation worked out very well indeed. The table rose in 2.4 sec., 0.4 sec. of this period being required to accelerate and 0.4 sec. to stop, the motor operating at full speed 1.6 sec. Recording ammeter charts show that this is accomplished without the motor requiring more than full-load current at any time. The controlling mechanism is entirely automatic, a movement of the operator's master-switch causing the table to rise and automatically slow down, and stop, while a reverse movement causes it to lower automatically, slow down, and stop. Although there is a solenoid-operated brake on the equipment, its time-lag is such that it never acts until the table has been brought to rest by generative action. The shape of the rotation-movement curve is again of value in that a few degrees of error in the stopping point, top or bottom, does not influence the position of the table to any extent.

The objection to the installation just described is the necessity for accelerating and stopping the counterweights at either end of the cycle, which adds considerably to the power required to operate. Therefore when the table for the blooming mill at Gary, Fig. 11, was designed, hydraulic counterweights were employed. The bell-cranks carrying the table are connected to hydraulic cylinders piped to the compression tank partly filled with air. When the table is down the air pressure in the compression tank over-counterweights the table by 25 per cent. When the table is up it is under-counterweighted by 25 per cent. This is accomplished by a proper proportion of air and water in the system.

Fig 12—Contactor type controlling panel for 200-volt, 250-h.p. direct-current motor used to raise and lower blooming-mill table

The Gary table moves 43 in., weighs approximately 250,000 lb. and makes a cycle in 3 sec. It is operated by a 250-h.p. motor running at 100 rev. per min. Immediately after completion of the Gary table, an interesting test was made to determine how closely the acceleration curve followed a true sine wave. A board carrying a paper chart was placed on the side of the table, and an electric bell with clapper removed and a pencil substituted connected on a 25-cycle circuit and arranged to make dots on the chart. Connected on a circuit of this frequency, it would make 50 dots per second. The distance between dots served as a guide in the compiling of a curve which, considered with the recording ammeter chart, shows the motor to be up to speed when the table begins to rise with any rapidity. Unfortunately a copy of this accelerating curve is not available for presentation at this time.

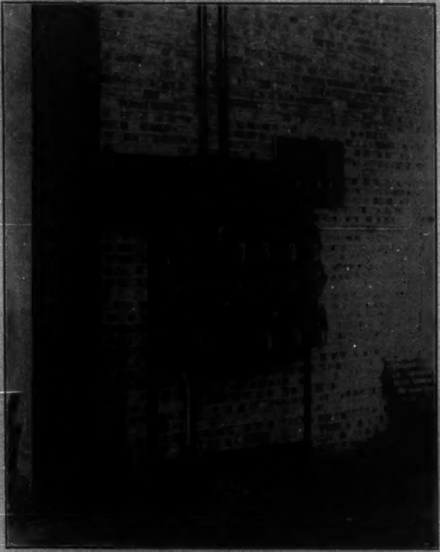

FIG. 13—Typical contactor type controller panel

FIG. 14—View underneath tilting table of three-high roughing mill, showing automatic limit switch and disc brake

FIG. 15—Hot bed with pulpit containing master switches for rake-offs and drag-outs

The Gary plant is filled with interesting automatic controllers. The completeness and effectiveness of the installation can be appreciated when it is considered that eight operators are able to turn out 100,000 lb. of rails per month. One of the most unique features of the plant is the automatic coal skips. Coal is delivered to the gas producer houses in standard railroad gondolas, from which it is dumped into a hopper. From here it goes through a crusher, and thence to the coal skips, which are of the double-balanced type, and arranged to dump into the bins, from which the producers draw their supply.

Fig. 16—Hot saws for sawing steel rails

When at the bottom, the skip-car automatically opens the chute-gate and rests on one end of a counterweighted lever. If there is any coal coming through the crushers, t will feed into the skip; if not, the entire equipment will remain inoperative. As soon as a certain quantity of coal has been fed into the skip-car it overcomes the counterbalance. This action starts the motor driving the hoist. In leaving the bottom position the chute is closed, and when the first skip-car is dumped, a second is at the bottom and ready to take coal. This automatic action continues as long as there is coal to be hoisted, a counting device for registering the number of trips being a fairly accurate indicator of the total tonnage of coal handled.

While this electrification of auxiliary apparatus has been going on, there has also been great progress made in the electrification of the rolls themselves. No electrical engineer is over-optimistic in believing that another 10 years will see the complete elimination of all motive power other than electricity in steel plants. In fact the only question to-day seems to be whether auxiliary apparatus of a reversing character shall be operated by alternating current or by direct current. Experiments now being conducted at Gary, where both types will soon be installed, may lead to some definite conclusions on this subject.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

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AUTOMATIC MOTOR CONTROL

BY H. E. WHITE

Of the various systems for controlling electric motors, none surpasses in interest and economic importance those which make use of electrically actuated switches controlled by automatic or semi-automatic means. A few years ago the drum controller was quite sufficient for any motor then in use. Since then the use of larger motors and the need for automatic features, unattainable in a simple manner with drum controllers, have resulted in the development of a great variety of magnetically controlled switches, and of various means for operating them in control systems.

At the present time, contactors may be obtained for handling the current required by the largest motors in use, and it can safely be predicted that in the future with even larger motors, air-break switches of the contactor type with magnetic blowouts will be used more and more for high-voltage current, hitherto thought controllable only by oil switches. Tests have in fact already been made showing that currents of 6600 volts can be successfully handled in this way.

Control by contactors is so universally adapted to service under special conditions, that the advantages which it offers over other devices are worthy of mention. Among these are:

a. The ability to control motors of any size with facility and with slight muscular effort.

b. The ability to control many motors from one conveniently chosen place.

c. The ability to control large motors from a distance with comparatively inexpensive connecting cables.

d. The ability, in conjunction with overload devices, to predetermine the current input to the motor, either during or after starting.

e. The ability to use sensitive devices, such as pressure gauges or thermostats to start motors operating machines such as pumps or blowers.

f. The ability to obtain " no-voltage release " and automatic re-starting features without additional complication.

g. The ability to secure interchangeability of parts to an extent not possible with any other type of control.

h. The ability to secure automatic stopping by limit switches to prevent overwinding or to stop the motor at predetermined places.

The methods by which these results are attained are best understood by examining the principles of operation with particular reference to which recent designs have been made.

The design of the contactor itself is the one thing on which too much stress cannot be laid, for the reason that on it falls the function of repeatedly opening and closing heavy currents in a reliable manner without frequent inspection or adjustment. Properly designed contactors have the inherent advantage of opening and closing quickly, thereby lessening the duration of the period during which the circuit-closing parts are making poor contact. This poor contact period results in a local fusion of metal with consequent wear. In fact, it is well known to those familiar with this type of apparatus, that the wear on the contacts is due almost entirely to local effects at the instant of making or breaking circuit and only slightly due to the vaporous arc formed. It is largely to this fact that the efficiency of motor control at high voltage is due, since the tendency to fuse the points of contact is proportional to the square of the current value, and not to the voltage. In case the currents are very high, recourse must be had to the use of refractory contacts for which the only commercially available substance is carbon. As to carrying capacity, there is a tendency in recent designs to secure it by forcing the contacts together at considerable pressure, but carefully made experiments show that the gain is greatest for the first increase in pressure on the contacts, so that it does not pay to attempt to carry the pressure too high.

Operation at high contact pressure results in the very important advantage that, when the recoil of the springs takes place at the time the contactor is de-energized, a much quicker opening results. In case the contactor is required to carry a very large current for a long time, an auxiliary laminated copper contact is used. The magnetic blow-out has been found equally effective for both direct and alternating current.

Voltage variation affects the operation of contactors in common with other devices operated by a solenoid. The pull of a solenoid varies approximately as the square of the voltage. As a consequence, any abnormal voltage conditions produce correspondingly increased effects on the contactors. This necessitates, in order that satisfactory operation may be assured, that the amount of copper used in the solenoid be sufficient to carry the current at full voltage without overheating, and to give at the same time pull enough at low voltage to ensure reliable mechanical action.

In the case of contactors operated by alternating current, laminated magnets are necessary to ensure operation without excessive heating. The action of solenoids on alternating current is quite different from their action on direct current. On alternating current, the tendency is towards constant pull independently of the position of the armature, with a corresponding reduction in magnetizing current as the solenoid closes. On direct current, the pull greatly increases as the solenoid operates. These peculiarities have a direct influence on the comparative action of the two types of contactor. The alternating-current contactor closes at a great speed, almost violently, while the direct-current contactor closes more leisurely, its self-induction tending to slow it down very noticeably. The heat generated in an alternating-current contactor is usually greatest in its iron magnetic circuit, due to the high densities required and to the alternating magnetic flux. In the direct-current contactor, the heat is generated entirely in the copper parts carrying current. One peculiarity of the alternating-current contactor is its tendency to hum. This can be reduced to an unobjectionable amount by the use of "pole-shading" devices, and contactors for operation on alternating current will consequently be more extensively used as they become better known.

In applying contactors to the control of motors a so-called *current-limit control* is usually employed. In all the simpler systems, the contactors are so arranged that as each one closes, it completes the actuating circuit for the next contactor, thereby causing the controlling resistance to be short-circuited step by step. One or more overload relays are so arranged that this progressive action will be interrupted without causing any contactors to be opened whenever the current exceeds a predetermined amount. As soon as the current decreases and the relays fall, the operation is renewed, until finally the motor is operating at full speed. In other cases, the contactors are arranged with their operating coils in multiple with the armature of the motor, so that as the motor starts, the increasing electromotive force across the armature will cause the contactors to operate one by one. This arrangement is known as the *counter-electromotive-force system.*

The last-named system is open to the objection that if the voltage of the supply system is not constant, the operation of the control is interfered with, the result being that if the voltage is low, the contactors may not close at all, while if the voltage is too high they will close too soon. This system is best suited for use with shunt motors and not so well suited to series motors, for the reason that the counter electromotive force of a series motor depends upon the current as well as upon the speed of the motor, so that there is a tendency to cut out all of the resistance in case a contactor closes prematurely.

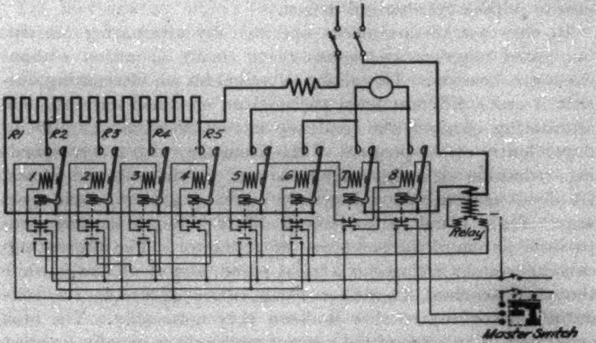

FIG. 1.—Current-limit control with single relay

A modification of this system, using potential relays in multiple with the starting resistance, is so arranged that as the current in the resistance decreases step by step, the relays will fall out and close actuating circuits for the contactors. This modified system is not open to the same objections as the counter-electromotive force system, and is substantially equivalent to current-limit control. In some cases, *time-limit control* is useful; that is, the contactors are arranged so that they will be energized in a given time regardless of other conditions. In this case an escapement or dash-pot is usually employed.

Still another type of control, which may for want of a better descriptive name be called *pilot-motor control*, uses some form of an electric motor to actuate a master switch. This motor can be controlled in any manner desired by overload relays or push-buttons. This system is the one generally used where the control is of a comparatively complicated nature, such as in printing-press work.

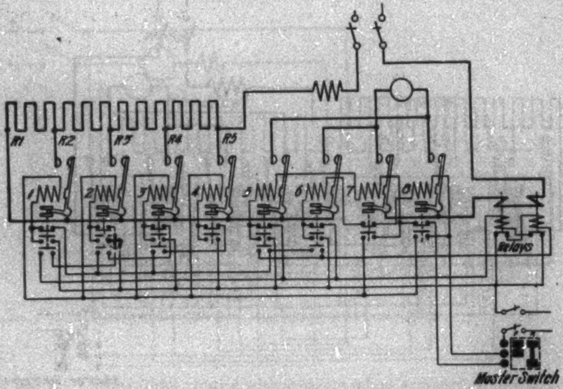

Fig. 2.—Current-limit control with double relay

It is interesting to note that the control of the 2000-h.p. and 6000-h.p. motors at Gary is of this type. In this place, it was used to avoid complicated interlocks on the contactors, which would otherwise have been required to secure the results desired.

The choice of control system to be used in a particular case will be determined by the special conditions governing each case. However, it can truthfully be said that while some of the other systems appear to be specially suitable in some respects, yet current-limit control is always better when all the conditions are considered.

Aside from the current-limit control obtained by the pilot-motor system, two comparatively distinct systems of current-limit control are now in common use. In one of these is used a single relay, with series and shunt coils. In this system as each contactor closes it completes a momentary actuating circuit for the next contactor, which then closes and establishes a holding circuit for itself independent of the momentary circuit above mentioned. The momentary actuating circuit passes through the contacts and shunt coil of the relay and causes the iron core of the relay to lift an iron core into the field of influence of the series coil, thereby interrupting the circuit at the relay just after the contactor has completed its holding circuit. When the contactor is fully closed, the interlocks establish a circuit to the next contactor through the relay, so that the above operation will be repeated for this contactor in the same manner, provided the current in the series coil of the relay does not delay the completion of the circuit by holding the iron core up. In other words, if the increase of motor current caused by the closing of the contactor is great enough, the core of the relay

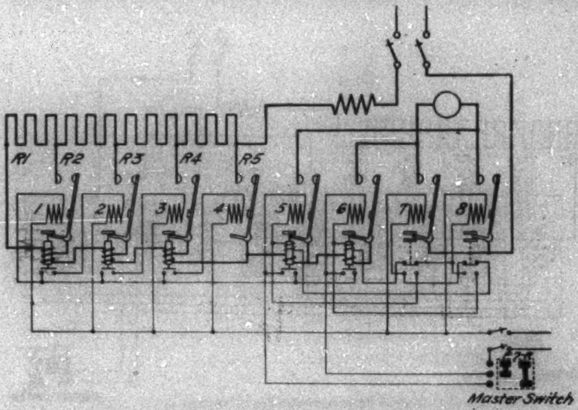

FIG. 3

will be held up and the "pickup" circuit for the next contactor will not be immediately completed. This system for reversible rheostatic control is shown in Fig. 1. The objection to this system is principally in the complicated interlocks necessary to perform the above operation. It has the advantage that the current-limit value for all of the contactors can be obtained by adjusting one relay. A further advantage lies in the considerable pressure with which the interlocks are held in contact. This advantage fits the system for use specially in transportation work and it is consequently most commonly used in railway service. A modification of this system using two relays and shown in Fig. 2, is an improvement in that less difficulty is met in adjusting the speed of the relays.

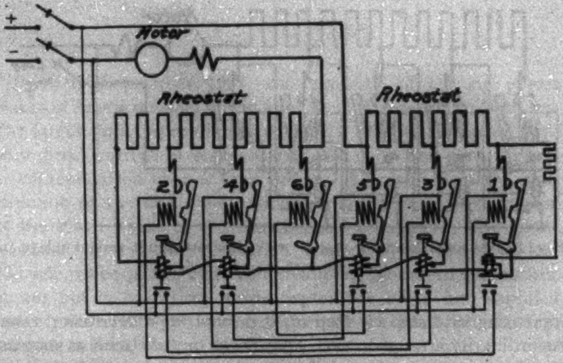

FIG. 4.—Current-limit control with separate relays arranged to introduce resistance into circuit step-by-step in case of overload

The second system makes use of a separate relay for each contactor. In its simplest form, each of the accelerating contactors includes as an integral part of itself an overload relay, which is held in the open position by a mechanical connection with the contactor until the contactor is closed, and is then allowed to drop and complete the circuit for the next contactor, only under the control of the current which passes through the contactor and the series coil of the relay. This arrangement is shown in Fig. 3, as used for a reversible control equipment.

A comparison of this system with the preceding ones will show its greater electrical simplicity. It will be seen that each series relay consists of two coils, and that these coils are so connected to the source of current and to the rheostats, that current flows through them both in series until the contactor is closed, after which current flows through only one coil. By this means, the relay is prevented from closing until the contactor has fully closed, and the increase of motor current resulting therefrom has become effective in the relay.

By using separate relays, acceleration can be secured at an

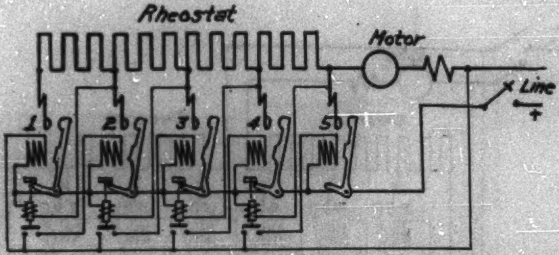

FIG. 5.—Automatic motor-starter with separate shunt-wound relays in multiple with starting resistance

increasing rate step by step or, if desired, at a decreasing rate. As ordinarily arranged, each relay is cut out of circuit as soon as the next contactor closes. In case, however, the circuits are so arranged that the relay is not cut out of circuit until the second next contactor closes, an equipment is obtained which has the interesting property of cutting resistance back into circuit step by step in case of an overload. The connections for accomplishing this result are shown in Fig. 4. Fig. 5 shows a motor starter with shunt type of relays in multiple with the starting resistance as described in the first part of this discussion.

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ELECTRIC POWER PROBLEMS IN STEEL PLANTS

BY R. TSCHENTSCHER

Prior to September 1904, the capacity of electric power plants in American steel mills varied locally from 200 to 3000 kw. The largest units were of approximately 1000 kw. capacity, and only direct current at a pressure of 250 volts was used. Plans in contemplation over a year before 1904 resulted in the construction of the first steel mill power plant of any magnitude at the south works of the Illinois Steel Company. This plant consisted of a 4000-kw. station composed of two 2000-kw. 25-cycle, three-phase, 2200-volt steam-engine-driven generators. It was put in operation during September 1904, and supplied two converter sub-stations, transformers for local alternating-current motors, and a 22,000-volt transmission line 10 miles long supplying alternating-current motors at a cement plant. Since 1904, many of the comparatively small electric power plants in steel mills have been increased to several times their original capacity.

Steel mills may be divided into four general classes; namely:

A. Finishing mills, or those that buy steel in the shape of blooms or billets and reduce them to a commercial form.

B. Steel-making mills, or those that buy iron and other materials needed in making steel. These mills are equipped with steel furnaces, and reduce their product to a commercial form.

C. Self-contained steel mills, or those that buy the raw materials necessary to make iron. These mills are equipped with blast furnaces, steel furnaces, and rolling mills for finishing the product.

D. Self-contained steel mills which also supply power to auxilliary plants, such as cement mills, or to other consumers.

A. The electrical problems differ somewhat in the mills as classified above. In finishing mills the electric plant usually consists of a direct-current, steam-driven station of from 200 to 1000 kw., supplying power for table motors, cranes, conveyors, lights, etc. No alternating-current power is used and the maintenance is a simple matter. The future problems of such a plant may result in the installation of motors to drive the mill rolls, replacing wasteful non-condensing engines and inefficient boiler equipment, and the installation of a modern efficient generating system, either steam-turbine or producer-gas-engine-driven (unless natural gas is available). The matter of installing storage-batteries and other refinements is a local one.

B. In existing steel-making mills the electric plant, though similar to that of plant *A*, is of somewhat larger capacity, ranging from 400 to 2000 kw. The power demand is also for a similar purpose, and a mixed alternating-current and direct-current system is not required. The future problems of such a plant are similar to those of plant *A*. The development of the electric steel furnace may, however, be such that a commercially feasible equipment might result and "cold metal" (pig iron, scrap, etc.) be converted into steel, thus doing away with cupolas or Bessemer converter installation. The electric power problem would then be materially altered, as described later.

C. In existing self-contained mills, the present problems are so diversified that a generalization is not as feasible as in the two preceeding classes. The electric plant problem is virtually a local one. A few general remarks may, however, be made. The electric power plants of such mills range from 500 to 10,000 kw. capacity, the larger capacity depending upon whether motor-driven rolling mills are in service, and other considerations of large power demand. In plants without motor-driven rolling mills a single direct-current system often exists, which, when properly arranged, makes for a decidedly simple and easily maintained equipment. The power demand consists of: 1. Ore-handling equipment, such as unloaders, conveyors, distributors, etc. 2. Sundry blast-furnace service, such as raw material supply cars, skip hoists, etc. 3. Steel-furnace application such as raw material, hot metal and scavenger cranes, charging machines, stripper cranes, etc. 4. And for the sundry rolling mill purposes as previously enumerated.

In mills without large concentrated power demand the problem of installing storage-batteries is a local one, and will depend frequently on the ore-handling equipment. If this be considerable, or if located some distance from the power plant, then questions of power-plant capacity or of voltage at the ore-handling plant may be solved advantageously by proper storage-battery installation instead of added direct-current generators in the former case and alternating-current generators and converters in the latter case. Where such ore-handling load does not exist, the station power fluctuations will in general not be over 10 or 20 per cent, and sufficient generating equipment only is needed. This equipment may be operated at a high load-factor, the necessary maintenance being attended to on Sunday when the rolling-mill load does not exist. The desirable arrangement of simplicity and uniformity of equipment which exists in every industry is most pronounced in mill work on account of the comparatively large repair expense, the inefficient operatives, and the costliness of delays. Therefore, a single generating system with simple distribution is desirable and feasible in plants of this kind.

In plants with motor-driven mills or other sources of considerable power demand, the problem becomes rather complicated. Again it is one of local treatment, though no doubt a few general principles may apply. The generating requirements will in most cases result in an alternating-current equipment. If the plant is an existing one and inefficient rolling-mill engine and boiler equipment is to be replaced by motors operated by means of efficient power generated in the vicinity of the blast furnaces so that blast-furnace gas may be utilized, then the commercial limitations will not usually admit of replacing the existing direct-current generating station. A second station must be built, either adjoining the direct-current station or at some more advantageous point. Proper electrical connecting apparatus between the two stations must be supplied. This will usually consist of a converter floating between the two station bus-bars. The advantage of this arrangement cannot be overestimated, as operating conditions will usually be such that at stated intervals (Sundays) either station may be shut down in whole or in part. The selection of proper alternating voltage may also be a local one, though the experience of the last 5 years shows that the increase of electrical application in steel mills is so rapid that a pressure of less than 6600 volts for local generation and distribution will no doubt result later in an unwieldy arrangement of switchboard and cable equipment and distributing feeders. The frequency of 25 cycles, now used almost exclusively, is most suitable, and nothing has yet appeared to indicate that a higher or a lower frequency would be more desirable.

D. It will no doubt be of some interest to discuss specifically a few of the electrical problems encountered in a large steel mill. For this purpose the plant of the Illinois Steel Company at South Chicago, Ill., will be outlined. This plant comes under classification *D*, previously referred to; namely, self-contained steel mills which also supply power to auxiliary plants such as cement mills, or to other consumers. Naturally enough, it is in such plants that the greater variety of electrical problems exists and where electrical application will be most extensive.

The South Chicago works of the Illinois Steel Co., is a good example of the self-contained steel mill. Its development during the last 5 years has been remarkable. Prior to September 1904, the electrical equipment of this plant consisted of a direct-current generating equipment of 2900 kw. at 250 volts pressure. Even at that time this was the largest electrical installation in an American steel plant. The electrical power demand consisted of that usually found in mills under classification *C*; namely, all classes of cranes, mill tables, and miscellaneous equipment, illumination etc. Since that time additional blast furnaces, ore-handling equipment, steel-making mills, finishing mills, and two cement plants have been added. Where steam engines had been used at blast-furnace skips, motors were installed and the cost of operating was reduced. Where steam engines had been used for ore handling and for all new ore-handling equipment, motors were installed, the output increased, and the cost reduced. Where new rolling mills were designed, motors on the main rolls were specified, with consequent increased tonnage at lower fuel and maintenance costs. Where new cement mills were installed, motor drive was employed throughout and power obtained by means of high-voltage transmission lines from an efficient power plant. Again the output was increased and the cost reduced.

Without going further into details, the electrical installations at this plant have during the last 5 years resulted in an equipment approximately as follows:

Number of motors, both alternating current and direct current	2,000	
Total motor horse power	75,000	
Total number of arc lamps	1,500	
Total alternating-current generating equipment installed	16,000	kw.
New alternating-current generating equipment being installed	9,000	"
Total direct-current generating equipment installed	3,000	"
Total generating equipment	28,000	"
Total synchronous converter (and transformers) and motor-generator equipment	6,500	"
Total storage-battery equipment	1,200	"
Total transformer equipment	31,000	"

The variety of the equipment may be judged from the various existing voltages; namely, 250-volt direct current; 110, 440, 1100, 2200, and 22,000-volt alternating current. This plant comes under the heading of "evolution plants"; that is, plants wherein steam and hydraulic equipment have been in process of replacement by electrical equipment. The solution of the various problems in such a plant does not result in the more desirable and simple systems which will be found in future new plants, for in the new plants the large variety of voltages mentioned above will surely be avoided.

One of the problems in steel mills now receiving considerable attention, and which in the future will be one of the real engineering problems, is the conservation of waste heat. The existing waste heat at open-hearth furnaces forms an enticing point of attack; this waste may be eliminated by replacing such furnaces by electric steel furnaces. These furnaces will be mentioned later. However, the waste heat at rolling mills does not as yet appear to be capable of satisfactory elimination. All steel before being rolled must be heated so that an even temperature, and hence even consistency throughout the piece, will result. Producer-gas furnaces are now used almost exclusively for this purpose. The stack temperatures are usually very high, being between 800 and 1200 degrees fahr. These temperatures may readily be reduced by passing the gases through suitable steam boilers to provide steam for turbine-generators. It is not at all improbable that instances exist where with proper installation of boilers, regenerators, turbine-generators, and roll motors, a rolling mill may be made a self-contained unit, obtaining from its present waste heat sufficient power to supply electrically the entire requirements of the mill, including the roll motor, table motors, crane equipment, lights etc.

The utilization of the energy remaining in the exhaust from non-condensing engines and from compound engines is now receiving serious consideration, the large amount of energy wasted in engine exhaust steam in non-condensing engines being roughly estimated at 50 per cent of the total available energy. The rolling-mill engine appears to offer a very desirable point of attack in this connection. However, the writer wishes to emphasize that there are many other places in most steel plants where this problem might better be attacked from the standpoint of permanent equipment. By attaching a low-pressure turbine equipment to the exhaust of a non-condensing rolling-mill engine, a premium is put on the retention of that engine in service. The superior operating and cost advantages of motor drive over reciprocating-engine drive (with accompanying boiler equipment) cannot be taken advantage of. The steam engine with a tail in the form of a turbine-generator will be much more difficult to get rid of. It would therefore appear that the other weak points about the mill should be first seriously investigated.

The steam-engine blowing equipment at many blast furnace plants consists of well built compound engines. The possibilities here for low-pressure turbine installation are very great. At a plant which recently came to the writer's attention, four blast furnaces receive blast from eight modern condensing blowing engines. Roughly, the amount of steam required by these engines is 300,000 lb. per hr. By the addition of less than 100,000 lb. these engines develop their required power with exhaust at 16 lb. absolute. These 400,000 lb. of steam would be sufficient to supply a low-pressure turbine-generator capacity of approximately 15,000 kw. The power station installation might consist of three 5000-kw. units. Sufficient power would be available to convert all the mills at this plant to electric drive.

One of the electrical problems at the plant of the Illinois Steel Company which may be of interest concerns the installation of additional generator capacity. A solution of the problem which contains many admirable points was an installation of a low-pressure turbine so designed that high-pressure steam up to full capacity will be economically utilized. Compound condensing reciprocating engines in the power station and in an adjoining blowing engine station will normally supply the steam for this turbine which will be of 9000 kw. capacity. Each compound engine will be so arranged that it may exhaust into the present condenser, or into the turbine main at slightly above atmospheric pressure. In case of insufficient low-pressure steam, the deficiency may be supplied from the high-pressure main, the turbine being so arranged that this high-pressure steam will be economically employed by means of a separate valve and nozzle chamber. Should no low-pressure steam be available, the full capacity at high-pressure steam may be obtained. The condensing equipment will be adequate, the yearly calculated vacuum averaging better than 1 in. absolute pressure. Reliability and economy are the predominating features in the installation. The operation will be watched with interest and it is expected that gratifying results will be derived.

Another problem at this plant which may be of interest was the improvement of the power-factor. The installation of alternating-current roll motors, miscellaneous small alternating-current motors, and the expansion of cement mills where the sole drive is by induction motors, have so affected the power-factor that at present the station power-factor is not over 70 per cent. The largest item in bringing about this condition is a load of approximately 7000 kw. of induction motors at a cement plant supplied by a 10-mile transmission line of 22,000 volts stepped down to 440 volts. Improvement of the station power-factor by corrective means at the cement plant at once suggested itself. This might originally have been accomplished either by the installation of direct-current equipment including motor-generators or synchronous converters or by the use of a considerable number of synchronous motors in place of induction motors. The operating conditions—character of service, cement dust, and inefficient operatives—make the former comparatively impracticable; the additional complication of miscellaneous operation of synchronous motors at proper power-factor by inefficient help makes the latter also undesirable. It is an ever present axiom in steel mill practice that the mill equipment should be simple, rugged, and easy of operation and repair. Whatever refinement and complication may be beneficial should be confined to engine rooms, power stations, sub-stations etc., where labor more skilled in maintaining the equipment may be employed. The foregoing therefore led to the decision that the cement-mill equipment should include the induction motor, the squirrel-cage type being used wherever possible, with simple starting apparatus such as step-down transformers with starting bus-bars, instead of local compensators and starters for each motor.

The question of power-factor correction resolved itself then into the installation of " synchronous condenser " equipment. In order to prove such an equipment commercially advisable, it is of course desirable to have the so-called condenser do mechanical work so that such proportion of its initial cost and operation and investment expense could be charged against it, making the charge for power-factor correction correspondingly less. However, mechanical work of sufficient magnitude did not exist at the cement plant, and the problem resolved itself into determining whether such a synchronous condenser equipment operating idle would prove a commercial proposition. A detailed study of this case was made; the following items give the points at which loss of energy would be reduced, a loss that could be expressed commercially, most of the factors being the components which tend toward combined efficiency;

a. At station generator fields, due to less excitation being required as the power-factor improved.

b. In station cables and switchboard equipment, on account of less current at improved power-factor.

c. In step-up transformers, due to improved power-factor.

d. In transmission line, due to less current and improved power-factor.

e. In step-down transformers for the same reason.

f. In step-down transformer wiring and switchboard equipment.

To offset the foregoing there is the energy required to operate the so-called synchronous condenser. With a delivered load of approximately 7000 kw. at 70 per cent power-factor, the over-all efficiency is approximately 83 per cent. The installation of two 1650 kilovolt-ampere synchronous condensers will raise this over-all efficiency to 87.5 per cent, the net gain of power being approximately 300 kw. which at 0.5 cent per kw-hr. represents a yearly saving of approximately $10,000. In addition to this, the power station capacity will be appreciably increased, due to the present engine capacity exceeding present generator capacity, and due in a small measure to decrease of excitation load. This gives the commercial aspect. The purely technical aspect of improved operation (regulation and control) due to improved power-factor needs but to be mentioned.

Where alternating-current motors are used to drive rolls, or for miscellaneous mill purposes such as for tables, cranes, etc., where now direct-current motors are used almost exclusively, the power-factor conditions will no doubt require power-factor correction; this may be accomplished by the installation of adequate synchronous condenser equipment. The commercial problem will here be rendered more simple, for considerable mechanical load in the nature of air-compressors, pumps, fans, etc., may be supplied to render the charge for power-factor correction materially less than that outlined above.

Before closing, it may be of interest to dwell upon another problem of considerable magnitude which is just becoming manifest. This refers to the manufacture of steel by means of electric power. The Illinois Steel Company has in operation a 15-ton electric furnace of the carbon-arc type. Three 750-kilovolt-ampere, 2200 to 100-volt, 25-cycle transformers are installed. That the making of steel by means of electricity will in the near future be an active commercial proposition in the manufacture of products where now crucible, open hearth, and Bessemer steel are used, is practically an established fact. This can easily be conceived to require power stations of a magnitude comparable with those of the largest lighting and railway plants. The writer believes the future will demonstrate that the country's largest power generating stations will be found within the confines of the steel plants. When one considers that a steel making furnace plant utilizing electric power to generate the necessary heat and having a capacity of 4000 tons per 24 hr. requires generating capacity of 20,000 to 30,000 kw., it is not difficult to conceive the magnitude toward which the future steel mill power plant will tend.

Let this thought be carried a little further to illustrate a plant wherein the application of electricity would be supreme. A 2,000,000-ton-per-year self-contained plant where coal, flux, ore, and other raw materials enter and where all classes of steel products, together with cement and the bi-products of coke ovens, leave the plant as finished salable products, might consist of a blast-furnace plant, a Bessemer converter plant, an electric steel-refining plant, a sufficient number of rolling mills, a cement plant, and a coke-oven plant. Such a plant would require electric generating capacity depending largely on the extent to which the finished product was carried. Consider the plant as finishing three-fifths its product as rails, one-fifth as plates, and one-fifth as structural shapes. The total electric power requirements for such a plant would be over 100,000 kw., and it is quite likely that such power could be generated without burning coal for power generation fuel purposes. The so-called waste gases of blast furnaces and coke plants and the utilization of other waste heat would supply more than the required fuel.

If now a plant be conceived wherein the product is further finished; for example, into tin plate, wire etc., a point may be reached where fuel must be obtained from sources other than the usually considered waste sources about the plant. The possible reduction of iron from ore by electrical application, or the manufacture of steel electrically direct from ore, are mentioned merely to show possibilities. The realization of such possibilities would be due to the designing and installation of power plants in comparison with which the foregoing mentioned equipment would be inconsiderable.

DISCUSSION ON "FUNCTION OF FLY-WHEELS IN CONNECTION WITH ELECTRICALLY OPERATED ROLLING MILLS." "ROLLING-MILL MOTORS." "ELECTRIC DRIVEN ROLLING MILLS." "POWER REQUIREMENTS FOR ROLLING HIGH CARBON STEEL OF SMALL SECTION." "ELECTRIC CONTROL FOR ROLLING-MILL MOTORS." "AUTOMATIC MOTOR CONTROL." "ELECTRIC POWER PROBLEMS IN STEEL PLANTS." FRONTENAC, N. Y., JUNE 30, 1909.

D. B. Rushmore: The subject of steel-mill work is certainly as important as anything at hand just now in the way of electrical development, and the most important requirement of steel-mill work is reliability. It is unfortunate that steel mills will to some extent buy on prices, but they are outgrowing that, because price always means a sacrifice of engineering features. The value of the output is so great in comparison with that of the machines which are used in its production that I think it is a wrong policy to make any very great difference in the equipment due to a difference in price, assuming that several alternative schemes are presented; that is, putting all the manufacturers on the same basis, the ordinary factors of competition, it seems to me, should in these cases give way. In reality, the man who is to control this situation should be the engineer of the steel mill and not the purchasing agent, because all manufacturers are to a large extent interested together in the success of electricity as applied to steel-mill work. At the present time there is no phase of the electrical development of steel-mill work more important than the control apparatus, for the steel mills must electrify generally if they are going to compete with those which have already done so and the controlling apparatus must be perfected so that the output of the mill will not be interfered with.

Mr. Tschentscher has touched the edge of the subject of getting power from the waste gas, but whether burning the gas directly under gas engines or burning it under the furnaces, or utilizing it in connection with steam turbines, is the best means of using it is still an unsolved problem. The design of gas engines for blast-furnace gas, for large powers, is by some considered somewhat of an open question; for while it is easy to figure out the supposed thermodynamic efficiency and the actual cost of the power which one will get, yet the development is not on such a basis that that is all which needs to be considered. What the steel-mill man wants is the net return on the gas from the operation of the steel mill; one of the factors is the output, and any interruption to service goes heavily against the cost of this, and has to be considered in estimating the cost of power. The proprietors of steel mills say they can handle electrically driven mills better than steam driven mills, for the reason that the piece always goes through the roll at approximately the same speed and it is in better shape to start the succeeding movement. The reciprocating apparatus is practically doomed, it seems, with the possible exception of the gas engine, and that has a threatening successor in the gas turbine. The use of gas turbines and the possible use of gas through the furnace and for steam turbine work, would practically remove all reciprocating apparatus from the steel mill.

Mr. Specht has picked out, perhaps, the most interesting problem in steel mill work, the fly-wheel capacity for special service. Unfortunately, this particular determination is not always left to the motor manufacturer. It seems that steel mill men, realizing that it is difficult to maintain normal conditions continuously on roll trains, often specify motor capacity and fly-wheel capacity much in excess of that needed for normal operation.

On the other side, there has been of late a carefully performed series of experiments to determine the power required for rolling steel, and some very interesting results have been obtained in regard to the variation of this power with the temperature of the piece. That is one case to illustrate the point that there is necessarily in all this class of work a very large margin, because the factors which enter into it cannot all be determined with precision, and are susceptible of considerable variation.

Brent Wiley: The following formula offers a convenient method of calculating the fly-wheel capacity of a system, and for an average case the run of the fly-wheel is figured as two-thirds of the total weight and the spokes and hub one-third of the total weight.

$$\text{Wt.} = \frac{F\,s \times 2 \times 32.2}{B}$$

Wt. = weight in pounds.

$Fs.$ = foot-pound-seconds = h.p. × 550 × sec.

B = difference of velocity squared at high and low speed in feet per second at radius of gyration.

I understand that originally the automatic features in the Indiana Steel Company's plant were incorporated in the motor-control apparatus and that later the system of control was changed somewhat; that is, to the extent of operating the controllers instead of automatically cutting in and out the resistances operating the motors with a permanent resistance.

K. A. Pauly: When the proposition for the rail-mill motors was being considered, the use of a small permanent resistance versus a variable resistance in the rotor circuit, to allow the fly-wheel to take the peaks, was discussed thoroughly; and it was finally decided that because of the ease of removing the automatic variable feature, it would be better to install the automatic control. Tests made after the apparatus was installed indicated clearly the use of a permanent resistance to be preferable. However, the direct-current contactor (because of the high inductance of its operating coils and the lack of opportunity of raising the impressed potential sufficiently above the operating potential by the insertion of resistance in series with the solenoids) is necessarily more sluggish than the alternating-current contactor. Possibly with the alternating-current contactor, recently developed, which operates more rapidly, there may still be something in the automatic acceleration and retardation over a small range. However, as the control with permanent resistance operates satisfactorily, and eliminates one of the possible troublesome parts of the control equipment, the automatic feature should be, at least for the present, omitted entirely.

With reference to Mr. Specht's paper, it must be borne in mind in determining the capacity of a fly-wheel to meet any given cycle, that the fly-wheel is employed as a means of reducing the operating cost of rolling. There are, therefore, many factors which must be taken into consideration in determining the most economical fly-wheel capacity. Among the important ones which are frequently overlooked are:

1. The cost of power, the first cost of the generating station and of the rolling-mill motor.

As pointed out in the paper, by the use of the fly-wheel we reduce the capacity of the rolling-mill motor necessary for performing the work, and of the generating station supplying the power, but at the expense of efficiency. When the cost per unit of power and the cost per kilowatt of generating capacity are high the economical size of fly-wheel is greater than when these costs are low.

2. The capacity of the fly-wheel is affected by the overload capacity of the generating units. For example, the most economical weight of the fly-wheel is greater where power for rolling is supplied from gas-engine-driven generators (which because of the better economy of the engines near the maximum load frequently have little overload capacity) than when the power is from a turbine station the momentary overload capacity of which is very large, due to the immense fly-wheel energy of its discs.

3. The capacity of the fly-wheel is affected by the number of mills or motors driven from the same generating station and, therefore, the number of intermittent cycles, which are combined to form the generator load curve. As the number of mills increases the peaks of the station load curve decrease. Beyond a certain point, depending on the overload capacity of the generating station, the advantages of the fly-wheel are confined to the rolling-mill motor, and the fly-wheel capacity may be reduced to a minimum

A fourth advantage of the fly-wheel that is difficult to capitalize at present, is the increase in reliability and life of the rolling-mill motor resulting from the reduction in mechanical and electrical strains in the windings.

A great many advantages have been put forth in favor of the steam turbine as a generating unit for supplying power for rolling mills. I think, however, little consideration has been given to the possibility of increasing the efficiency of the rolling by the use of turbine-driven generators.

M. O. Dellplain: There is a matter which might be brought up at this time and one regarding which steel-mill engineers would probably all appreciate information, as it has to do with the only portion of the mill in which electricity has not as yet been positively accepted. I refer to the use of motor-driven air compressors for operating the hammer shop. The successful application of air for use in the hammer shop would mean practically the complete solution of the problem of the electrification of the steel mill.

Clark S. Lankton (by letter): Mr. Specht says that in motor-driven sheet mills the automatic control can not be used to advantage, that it would do more harm than good. I wish to take the ground that a proper control for induction motors driving sheet mills is a very much desired feature. The advantages of control do not make themselves felt in the way it was first intended they should; that is, to smooth out the peaks. This is not practical because, as Mr. Specht says, the fluctuating load is too quick for the automatic feature to act. The control is practical, however, in that it affords a large amount of protection.

A sheet mill has from four to ten stands of rolls connected to the same shaft and each set of rolls is manned by a separate crew, each working independently of the other, hence the total load on the motor is made up of as many components as there are mills. Each unit requires power over and above its friction load but a relatively short period of the total time; that is, the actual time that iron is being passed through the rolls is short, say one-eighth of the total time, or 3 hours out of 24.

The different crews have no relation to one another, and, with several mills operating, combination loads of almost any magnitude might result. A motor of gigantic proportions would be required to meet every possible combination of peak loads which occur, although the square-root of the mean-square load would not require so large a motor. The advantage of a large fly-wheel reserve is apparent.

It has been suggested that a permanent amount of external resistance be inserted in the circuit of the motor secondary in order to obtain slip enough to allow the utilization of the fly-wheel energy. By this method the motor would run with lessened efficiency, not only at times of heavy load, but also at times of medium and light loads, which is by far the greater part of the time. The efficiency could be improved by installing a larger motor which would allow of less slip, but, on the other hand, it would have increased capacity and greater first cost.

It would not be so bad to sacrifice efficiency for a few seconds during a heavy jam, and, with proper control, it would be possible to hold the motor to the load until the load became excessive;

then to allow the motor to give way and receive aid from the wheel—thus the lower efficiency would be operative only occasionally and then for only a few seconds at a time. I have seen a sheet mill successfully operated in this way and no trouble apparent in control for some period of time.

Let us give up trying to smooth out every fluctuation, but do not discard the control feature. Set the control to operate at a high load, however, and use it as a protection against the unusual peak rather than to level all peaks. If the source of supply is a little larger than the capacity of the mill, these smaller fluctuations will not be troublesome, and because of their frequency with the added number of mills the resulting load approaches a continuous load.

H. C. Specht: The amount of fly-wheel effect of an induction motor, with wound rotor particularly, is fixed mainly by the design itself, and it is very difficult to add more fly-wheel effect unless the additional weight is placed on a smaller radius, where it is not as effective. Further, it is not often desirable for mechanical and other reasons to put all the fly-wheel effect in the motor. Assuming, for instance, that a motor has to drive certain machinery, and a specific fly-wheel effect is desirable, also that at some later date the machinery driven by the motor is to be changed or the motor has to be used otherwise; under these circumstances the fly-wheel effect first placed in the rotor may be no longer the right one. Then the motor would have to be changed, and in such a case it would be more desirable to make the motor of normal design in the first place without particular reference to the required fly-wheel effect. Any additional necessary fly-wheel effect is then secured by coupling to a separate fly-wheel. A further advantage of this arrangement is that the motor is relieved of any sudden shocks.

The equations which I give for the torque curve have also been worked out by Mr. I. E. Hanssen in a similar way, and agree exactly with mine.

Chas. F. Scott: The problem of power generation which has been presented, the peculiar conditions of power supply through gas at the steel mill, the severe conditions of fluctuating load—all these bring severe and peculiar conditions which must be taken into consideration and treated in a broad way by the engineer who is handling them. It was said by one of the speakers that the electrical engineer in the steel mill is only 40 per cent an electrical engineer and 60 per cent a business man. I am rather inclined to think that some of the things classed as business in that position are properly engineering, engineering in the broader sense, as the engineer must take into consideration not merely the formulas on which his apparatus is based, not merely the electrical phases of his apparatus, but that larger engineering consideration which applies means to the accomplishment of results. This larger view also includes the mechanical conditions in which the various elements are controlled by the electrical apparatus, and the various operations in which the electrical apparatus simply plays a part. There are other considerations. He must be human, and must be able to handle the rather obtuse mill operators who do not like to do anything differently from the way in which they have been accustomed to do it. All this emphasizes the fact that the steel mill engineer must be a pretty large and progressive man.

The matter of power-factor was referred to. Power-factor has a rather disagreeable reputation, and when one finds it attached to anything, it is usually regarded as quite discreditable. Mr. Tschentscher takes pride in telling that he has been able to save $10,000 a year in wiping out this power-factor, and I take it this is a case where auxiliary machines are fully justified. They are installed at the end of the transmission line, so they relieve the line of carrying an extra amount of current. But, after all, has he accomplished something which is large and fundamental? He saves $10,000 a year on 7000 h.p. of motors, or something less than $1.50 a year per motor horse power. That is equivalent to the saving of $1.50 a year in the power supplied to the motor for each horse power rating. I do not know what the power is estimated as costing; it is probably fairly high for the rated horse power of the motor, because motors in the cement mill are called upon to do fairly continuous duty. If the power costs $15 per year, the saving would be about ten per cent on the power; that is, the power would cost $15 instead of $16.50. If the cost were $30 a year, it would be a saving of about five per cent, so that in this case the power-factor of the motor is a matter which would increase the cost of power by five per cent or ten per cent. If direct-current motors were used, and the power-factor avoided by discarding the induction motor, there would be new objectionable features introduced, such as the loss in transmission apparatus, synchronous converter, or motor-generator, as well as a higher first cost and attendance.

In applying electricity to steel mills the first thing that is usually thought of, the thing that has been given large consideration here to-day, is the supply of power. The supply of power, considered in comparison with the total cost of production, is probably a relatively small factor, the larger matters being considerations of operation, of continuity of service, of applying the power effectively. If the motor can work more effectively—if, in conjunction with the mill which it operates, it can do better service, or produce a saving in labor, or more uniform or greater output—then these savings will far overbalance the saving in power, will far overbalance the fixed charges on the first cost of the motors. Consequently, effective operation is a point of far more value than the others I have mentioned.

I have been interested in Mr. Friedlander's paper in the description of the operation of certain mills by motors, and in the number of points which be brings out showing the indirect advantages of the motor, not simply because it does what the engines already do or could do, with possibly a saving in the power cost, but also is doing things which the engine did not do and could not do. In his second paragraph he tells us that the rolling mill drive has taught us how to get the best relation among rotating masses, speed, time, and horse power. It has helped the roll designer to calibrate rolls in such a manner that the power characteristic for all the passes is uniform, thereby avoiding high power peaks, decreasing the size of the prime-mover, and reducing first cost and fuel consumption. The watt-hour meter warns the roller that bearings or rolls are becoming tight and hot, or that steel is causing excessive friction in the passes, often due to overfilling, cold steel, or faulty calibration, thereby guarding against damage to the rolls and bearings. The meter indicates that lower heat, greater elongation, and especially change of profile in different directions, increase the power required at the rolls much more rapidly than do chemical hardness, high tensile strength, or large draughts.

After analyzing the conditions in reciprocating engines for this work, we find that the characteristics of the electric motor are much better. A little further on he says that heavy reciprocating engines cannot run at such high speed, and must be connected to the rolls by means of gears, ropes or bolts. Again:

> To obtain accurate information as to the exact power requirements for rolling steel, indicator diagrams were taken on reciprocating engines doing similar work, but these in many instances were misleading. * * *. With the use of electric motors in place of reciprocating engines, the problem of reversing rolls becomes much simpler and better, in regard to manipulation, fuel consumption, and cost of maintenance.

Now, these are all indirect things, points of inherent superiority of the electric drive over the steam drive, points which show a reaction or interrelation between the motor and the mill, which indicate that the motor is going to have a vital effect upon mill work because it does what the engine cannot do.

John C. Reed: Have controllers ever been designed for obtaining dynamic braking in connection with an induction motor?

H. E. White: So far as I am aware, there is no method of applying current to the induction motor that will bring it to rest, without a tendency to start it in the opposite direction. In some installations now being made, current is being applied with reversed phases, and some means is used to shut off the reverse current when the motor stops.

In reference to Mr. Wiley's question concerning the automatic features of the control of large induction motors, Mr. Pauly has given the principal points. From the controller designer's standpoint it appears to be very desirable that the arrangement of the control be chosen so that a permanent resistance can be left in the motor circuit. It is a simple matter to arrange it so that the permanent resistance can be changed by changing the position of the master controller.

If automatic overload features are used, and a number of excessively heavy loads occur at short intervals, the speed has a tendency to be greatly reduced; if, however, resistance is left in permanently without automatic overload features, the torque will increase to the limit of the motor and the work will be carried through. I think that with the use of alternating-current contactors instead of direct current we would not have very much difference in action in either case. If the motor is running synchronously with all resistance cut out, the current will increase very greatly with a slight change in speed, but it is difficult to get automatic overload devices that will operate before the current shows an undesirably great increase.

I should have said no method of applying alternating current. The large induction motors at Gary are now equipped to apply direct current to the stators of the motors, and this will stop these motors and fly-wheels in a few minutes, when they might run unretarded for as many hours. I understood the question to apply to alternating current only.

In my experience with contactors for alternating current, which has recently been extensively increased, I find that under all the conditions of design with which I am familiar they permit of very quick closing. While I have no doubt that an oscillogram of the operating current would show some very curious things, yet the contactors I am familiar with always close practically instantaneously; it is easy to see that this must be so, for even on 25-cycle current the time between the minimum and the maximum current value is only about one one-hundredth of a second.

A. M. Dudley: Mr. Parker asked about the relative desirability of having the entire amount of fly-wheel effect desired rotating at the same angular velocity as the motor, or connected to the motor by belting or gearing, and running at a higher speed. Mr. Specht, I believe, did not quite cover that point. Mr. Parker's statement is true, that there is no advantage in the one over the other, as far as the actual weight of the active material in the fly-wheel itself is concerned; that is to say, the same weight will have to be kept but disposed differently. It has been my experience, however, that when the extra weight is taken out of the motor structure and not carried on the motor spider, it is possible to build the entire motor somewhat lighter. It seems to me there might possibly be some advantage in that direction.

Mr. White said that he believed there was no method of employing dynamic braking in connection with the wound secondary motor and bringing it absolutely to rest. This holds good unless direct current is used in connection with the windings; that is, direct current is introduced into one member or the other, in which case the same effect is obtained as on a direct-current machine.

H. K. English (by letter): Mention is made of the fact that the time required to accelerate or decelerate a heavy fly-wheel must not be overlooked. This is especially true in plate-mill work, where it is often desirable to increase the rolling speed considerably after the first heavier passes are through. As an illustration, take the example used in the paper. Should it be decided to change at the end of the ninth pass, from 52 to 104 rev. per min. for the remaining 10 or 12 passes, the 120,000,000 lb-ft.[2] fly-wheel would obviously be out of the question on account of the time and energy required to accelerate it to 104 rev. per min.

Again, it is an advantage, where possible, to have in the fly-wheel enough stored energy to clear the rolls should the power fail, or should the motor, for any reason, become momentarily inoperative. Referring once more to the data sheet, pass No. 9, Fig. 3 represents some 11,700,000 ft. lb., while a 20,000,000 lb-ft.[2] fly-wheel running 52 rev. per min. has but 9,250,000 ft. lb. stored energy. Should the power fail just as the steel is entering for pass No. 9, the rolls would not be cleared, making it necessary to loosen the rolls, reverse the motor, and back out the steel. This consideration is of more importance in a rail mill with a number of motors in a train, and large quantities of steel, in different stages of completion, in the mill at one time.

I mention these two points to emphasize the fact that the choice of a fly-wheel for any given installation will be governed, more by an all-round practical consideration of the case in hand than by any mere efficiency calculations.

There has just been completed a series of tests on an electrically driven rail mill which has recently been put in operation, and it has been very gratifying to see how closely the test values check the original calculations both as to power required for the several passes, and as to motor performance. In view of this fact, and the successful record this mill is making, it would seem that Mr. Specht is scarcely justified in assuming that careful study has not been given these first installations.

Arthur C. Eastwood (by letter): I believe attention should be directed to the conditions under which controllers must operate in a steel mill. I refer to the controllers described by Mr. White and Mr. Henderson in which a separate series relay is associated with each contactor in a controller, the closure of each successive contactor being governed by the current flowing through the motor, and each series relay being susceptible of individual adjustment.

In steel mills I believe it is common practice when records are in view to doctor the controller relays with bolts, nuts, and wrenches. In other words, under mill conditions a controller designed automatically to limit the current input of a motor may, in a few seconds, lose all semblance of current-limit acceleration, the cutting out of the resistance being governed solely by the time element of the contactors or magnetic switches. Further, the larger the number of adjustments provided, the greater the chance for maladjustment where uneducated and electrically unskilled rollers, table men, shear men, millwrights, etc., have access to the controller, and where the adjustments are purely mechanical, consisting in weighting a plunger or tightening a spring. Even in the hands of a skilled electrician, to secure accurate adjustment of a controller having a relay on each switch, a recording ammeter is almost a necessity.

As to the advantage found by Mr. Henderson for the multiple relay system of acceleration; that is, the ability so to adjust the relays as to interpret the commutation curve of a motor—it is conceivable that this is an advantage under some conditions but not one which is likely to appear in a steel mill. A steel-mill engineer would hardly install a motor so near the limits of commutation that special provisions would be required to help it out, and if such a motor were inadvertantly installed it should be very promptly torn out and a motor installed better suited to conditions.

There is another system of automatic relay acceleration not described by either Mr. White or Mr. Henderson, which was specifically designed to meet conditions as they exist in steel-mill service, and it is extensively used in many of the largest steel works in the country. In this system only a single accelerating relay is employed. Hence there is but one adjustment; and accurate adjustment as to maximum accelerating current can be determined by the use of an ordinary indicating ammeter. The relay has a single winding of coarse wire, controls only a single pair of contacts, and in service is ordinarily enclosed in an iron box which can only be opened by a key in the form of a special horseshoe magnet with which only those properly qualified to make the adjustment are provided. This prevents tampering with the apparatus by those not properly equipped to adjust it.

Further, the adjustment for varying the maximum accelerating current is electrical and not mechanical. Consequently an unskilled worker who would not hesitate to hang a weight on the ordinary form of relay is very likely to keep hands off, since he will hesitate to tamper with electrical connections.

The adjustment is obtained by varying the portion of the total motor current which passes through the winding of the relay, and is accomplished by shunting the winding of the relay, The constants of the relay itself remain fixed. It will always lift its plunger when a certain definite current flows through its winding. Assuming this current to be 50 amperes and the desired maximum motor current to be 100 amperes, the relay will be so shunted that one-half of the motor current will pass through its windings. If the desired maximum motor current be 200 amperes, the shunt will be so adjusted that one-quarter of the total motor current will pass through the winding of the relay.

This method of shunting the winding of the relay not only provides means for adjusting the maximum accelerating current in case of a given motor and controller, but also permits of adapting a standard relay for use with motors varying widely in capacity. In an equipment installed in one of the large steel works of the country, embodying some 65 automatic magnetic controllers for motors varying in size from 25 to 250 h.p. duplicate relays were used in all the controllers, the adjustable shunt in each instance adapting the relay to operate at the required maximum motor current.

A diagram of connections of this system of automatic acceleration is shown in Fig. 1, in connection with a reversing controller for a series-wound motor.

A is the armature and *F* the field winding of the motor.

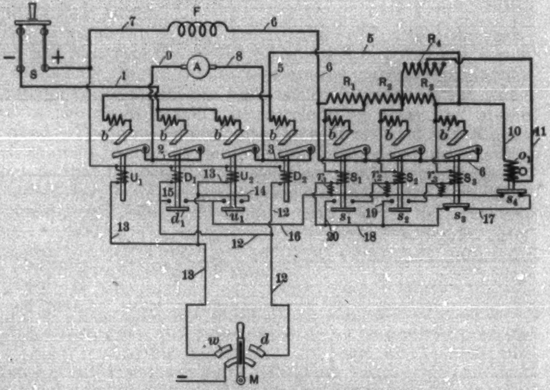
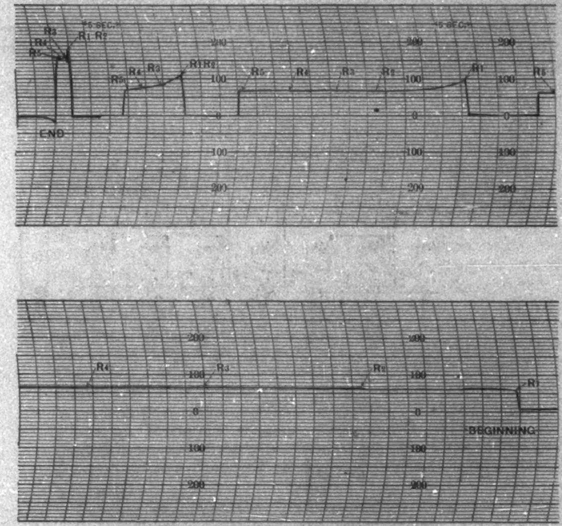


Fig. 1—Automatic accelerating controller

*R*1, *R*2, *R*3, and *R*4 are sections of resistance. *D*1 and *D*2 are reversing switches which give one direction of rotation, while switches *U*1 and *U*2 give the reverse direction of rotation. *S*1, *S*2, and *S*3 are magnetic switches controlling the sections of resistance *R*1, *R*2 and *R*3. *M* is the master controller through the operation of which the motor is started, stopped, and reversed. *O* is the accelerating relay which governs the closure of the resistance controlling switches *S*1, *S*2, and *S*3. *R*3 is an adjustable resistance which shunts the winding of the relay *O*. It will be seen that the main current flows from positive through the field *F*, the resistances *R*1 and *R*2 where it divides, a part flowing through the resistance *R*3, the wire 5, the reversing switches, and armature of the motor to negative, and the remainder flowing through the adjustable resistance $R4$ and the winding of the relay O to the wire 5 where it joins the other path. Obviously, the portion of the motor current which flows through the winding of the relay may be adjusted by altering the relative resistance of the two paths. It will be noted that resistances $r1$, $r2$, and $r3$ are associated with the windings of the switches $S1$, $S2$, and $S3$. These resistances are so proportioned that when in circuit with the winding of a switch-operating magnet they will not permit sufficient current to flow to cause the switch to close, but will permit sufficient to flow to hold the switch closed after its plunger has been raised. The function of the contacts of the relay O is to control the resistances $r1$, $r2$, and $r3$. When the plunger of the relay is down, these resistances are short-circuited; when the plunger of the relay rises, these resistances are cut into circuit with the windings of the switch-operating magnet with which they are associated.



ACCELERATION CURVES OF 25 H.P. 220 VOLT SERIES MOTOR WITH AUTOMATIC CURRENT-LIMIT CONTROLLER.

FIG. 2

Assuming that the switch S-1 has closed, and in closing has produced a current value which causes the relay O to lift, the winding of switch *S*2 then receives current through the resistance *r*2 which, as previously mentioned, will not permit sufficient current to flow to cause the switch to close. It should be noted, however, that a small current flows through the winding of the switch which is about to close, thus partly building up the magnetism of its closing magnet and leaving the switch prepared to close promptly. This largely eliminates the time element of the successive switches in closing. When the motor has accelerated, thus reducing the current flowing through its windings to the proper point, the relay drops, thus short-circuiting the resistance *r*2 and permitting the switch *S*2 to close. Switch *S*3 is controlled in a similar manner.

The relay *O* is provided with but a single pair of contacts, and only a single electrical interlock is associated with the control circuit of each switch.

The curves shown in Fig. 2 were taken with a recording ammeter, and illustrate the acceleration of a 25-h.p. 220-volt series motor in which the maximum accelerating current, and hence the time of acceleration, has been varied by varying the resistance of the shunt round the accelerating relay, as above described. These curves illustrate the wide range of adjustment which may be secured in the total time of acceleration, showing as they do that the period of acceleration may be varied from 65 sec. to less than 2 sec. the accelerating current in the two cases being respectively 60 to 65 amperes and 160 to 165 amperes. These curves also illustrate the sensitiveness of the accelerating relay, showing that it will raise and drop its plunger with current variations of less than 5 amperes.

As to the Hulett unloader, which was described by Mr. Henderson as offering particular advantages for automatic control, the writer can speak with some authority as he designed and installed the controlling equipment for the first electrically operated Hulett unloaders in 1902 and 1903. On the first Hulett unloaders (installed at Conneaut, O.) the machines were driven throughout by steam and hydraulic power. The next machines (the first three installed on the Lackawanna Steel Company docks at Buffalo, N. Y.) were driven electrically with the exception of the bucket-closing and rotating mechanisms, which were operated by means of hydraulic cylinders. This necessitated mounting on each machine a motor-driven pressure pump operating at 1000 lb. pressure, a motor-driven air compressor, an air-hydraulic accumulator, and an elaborate system of high-pressure piping, swivels, valves, etc., which was a prolific source of trouble not only in itself but on account of damage to electrical apparatus which occurred through frequent leaks in the hydraulic system.

Hydraulic power was selected for the operation of the bucket because of the absolute necessity of limiting the torque or pull which occurred in closing and rotating the bucket. The bucket of the unloader is suspended from a structural leg some

40 ft. in length, as illustrated in Fig. 3, which shows the bucket of one of these machines in the hold of the steamer "Wolvin". In scraping ore from between hatches, or in case the bucket should entrain more ore than it could hold, or if the bucket happened to foul a stanchion or other obstruction, obviously the torque or pull must be limited, as the bucket has a leverage of some 40 ft. on the frame of the machine, and a wreck would result if a definite maximum pull were exceeded. An electric motor, with its ability to increase its torque to perhaps ten times full-load value before stalling, appeared altogether unsuited to the purpose.

After experimenting with a number of other schemes, a form of controller was devised by the writer which gave to the operation of a motor substantially the characteristics of a hydraulic cylinder. In this controller a series relay was introduced, which weighed the load and when a given normal current was exceeded, automatically cut resistance into the motor circuit, thus limiting the current, and consequently the torque, to a safe maximum value. The arrangement was such that current would not be cut off from the motor when an overload occurred, but the current would be automatically limited and the current limiting resistance would be automatically cut out when the load was relieved. This arrangement successfully displaced the hydraulic

FIG. 3—Bucket leg of an ore unloader working in the hold of a steamer

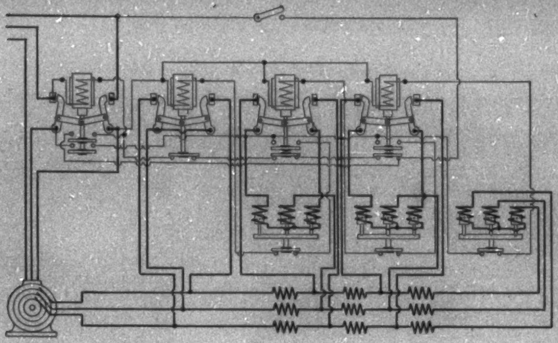


FIG. 1

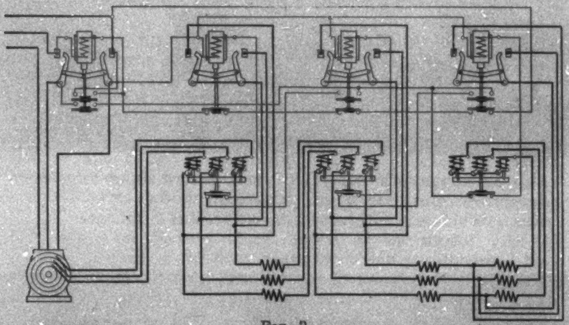


FIG. 3

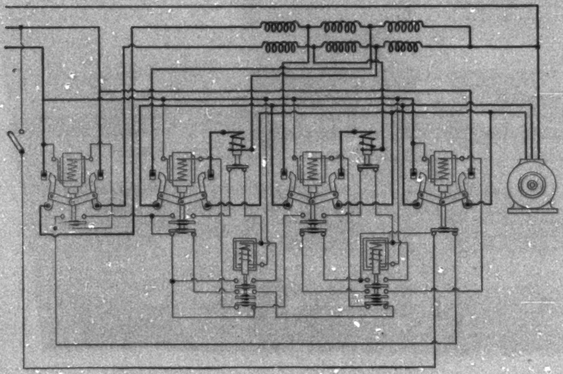


FIG. 4

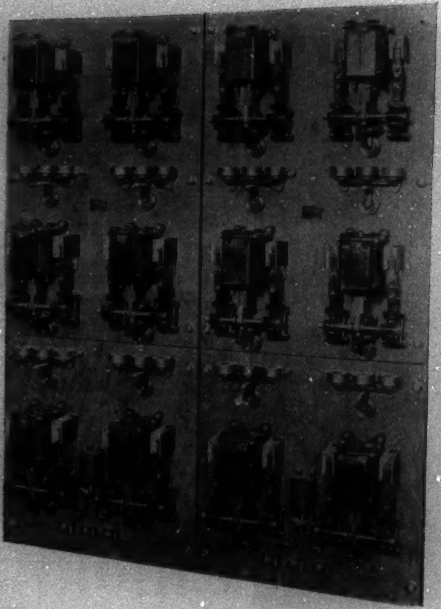


FIG. 2

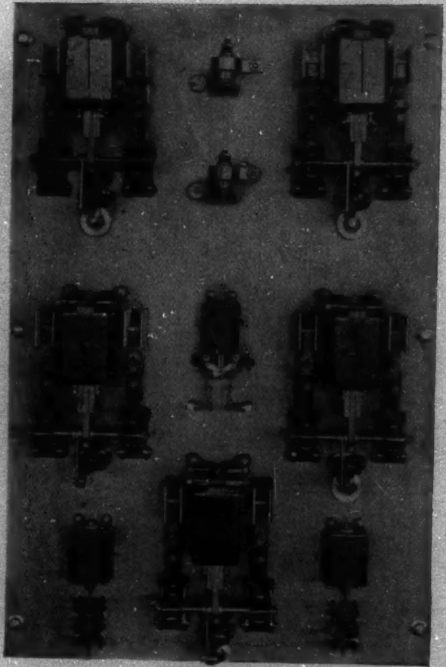


FIG. 5

cylinder and all subsequent Hulett unloaders have been similarly equipped. The Hulett unloaders on the docks of the Indian Steel Company at Gary are equipped in this way, and are also equipped throughout with the system of current-limit acceleration above described.

Arthur Simon (by letter): Mr. Specht states that the automatic regulation of resistance in the secondary circuit of the slip-ring type of motor is not desirable on account of the sluggishness of the controlling apparatus, and he therefore restricts himself to the calculations of a slip-ring type motor with a fixed resistance and a fly-wheel. This method of operation is undoubtedly the simplest, but by no means the most economical. Mr. Specht agrees that theoretically the variable resistance method with a lighter fly-wheel would be preferable, but the writer is not convinced that it will be impossible to produce a controller which will follow quickly the changes in load on the motor.

As far as the writer is aware, the controllers which were designed to accomplish the automatic regulation of the secondary resistance were all influenced primarily by a current relay connected in the primary circuit of the motor. Furthermore, most of these controllers, or all of them, were of the pilot-motor type. In other words, there were several elements, which, with regard to the cycle of operation, were connected in series. The ultimate result was obtained only after the successive operation of all parts, which necessarily must consume considerable time. The writer is satisfied that it would be possible to connect proper relays in the secondary circuit of the motor. As the secondary current is the first quantity which is influenced by a change in speed, that is, the change in load, it is only logical to accomplish the control by means of a relay in the secondary circuit. This relay should influence directly contactors which control secondary resistance, and this method will give entirely satisfactory results as far as the speed of response is concerned, and, furthermore, be still more desirable for other reasons, which will be discussed in the following:

Mr. White says that the 6000-h.p. motors at Gary are controlled by a pilot motor which is influenced by a current relay. A diagram of this control scheme was published in the "*General Electric Review*", and I note that the current relays are connected in the primary circuit. For the same reasons as stated above, these relays should be connected in the secondary circuit of the motor, and it is obvious that the scheme as shown in his Fig. 1 is preferable to the pilot-motor control. Fig. 2 shows a double panel of this type. With the pilot-motor control the entire operation of the motor, and with it the operation of the plant, depends upon the pilot motor and the current relays controlling it. The failure of any one part will shut down the motor entirely, while with the control scheme shown in the diagram all parts are interchangeable and the failure of one element does not necessitate the shutting down of the entire plant for repairs, but merely the short-circuiting of this element while the motor can then operate with a reduced number of accelerating speeds, and it is still possible to keep the mill running while repairs on the part which is in trouble are being made. This control scheme also reduces the time element necessary for the action of the automatic slip regulation. If such automatic slip regulation in connection with a flywheel is desired, it will of course be necessary to change the connections of the relays somewhat, for instance, as suggested by Fig. 3.

Mr. White further states that the current relay control is undesirable for squirrel-cage motors started with potential starters. The writer cannot share this opinion and submits, herewith, in Fig. 4 a connection diagram, and in Fig. 5 a self-starter for squirrel-cage motors controlled by current relays. The objection to the constant-time-element control is that the motor is switched from the starting to the running tap of the transformer at a variable speed, which causes considerable variation in the surges on the line. Suppose that the motor-speed at which same is connected to full line voltage was 10 per cent below normal and the normal slip of the motor was 4 per cent, in this case the momentary current inrush would be 250 per cent of normal. Such slight variations in the speed when switching over are entirely possible with the constant-time-element control, while it is possible to set current-relay controllers very closely, say, within at least 10 per cent, which will entirely avoid the danger of momentary overload on the line to which the motor is connected, or the tripping of the circuit-breaker during starting.

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SOME CONSIDERATIONS IN DESIGNING HEAVY CAPACITY FUSES

BY LOUIS W. DOWNES

The conditions governing the operation of the open link fuse and of the enclosed fuse are radically different. That such a difference exists is due largely to the presence in the latter of a confining case of relatively small dimensions and of a material, the porous filling, which acts in two capacities: first, to disintegrate the vaporized metal; second, to condense or cool it and render it non-conducting.

The filling, on account of its porosity, allows the expanding gases to escape in every direction and their continuity is thus broken up. Furthermore, the gases coming in contact with a substance, which is at a temperature many hundreds of degrees lower than that of the gases, are condensed and cooled and thereby lose their conducting power.

This feature is wholly absent in the open link fuse. The gases formed at the rupture simply expand in the atmosphere, and a continuous stratum of conducting vapor is formed between the two terminals of the cut-out in which the fuse is mounted. There is nothing present to disrupt, break up, or condense this vapor other than the air, which can act only in a slight degree and relatively slowly; and in this condition we find the explanation of the tendency shown by the open link fuses, whether multiple or single strip, to arc most violently when subjected to a short-circuit.

On the other hand, the gases so formed in the open link fuse are dissipated with greater or less rapidity into the surrounding atmosphere, and since there is no confining casing, no opportunity exists for the violent explosive action which will occur as a result of the expansion of the metal vapor in the enclosed fuse, if it is not properly designed.

The conditions to be met in the design of an enclosed fuse are therefore materially different from those imposed by the open link fuse. We not only have to suppress the arc but we have to handle the tremendous expansive force of the vaporized metal within a comparatively confined space.

Further, the radiation of the heat from the metal of the link takes place in an entirely different manner. With the open link the heat dissipation is directly from the surface of the metal. In the enclosed fuse, the heat dissipation must take place by conduction through the porous filling to the surface of the tube, so that in enclosing a fusible link and surrounding it with porous material we have modified practically all the conditions of operation.

The most serious difficulty that we have to contend with in the design of the larger capacity fuses is that of explosion, and this difficulty becomes greater as the capacity is increased. The problem is largely one of what we term "volume ratio and distribution;" that is to say, the relation which the volume of the fusible link bears to the volume of the enclosing tube and the distribution of the metal in the filling. Were it possible to carry out the same relationship in the large capacity fuses as that employed in the small capacity fuses, the problem would be too simple and would possess few features of technical interest. It is obviously impossible, however, to maintain this same ratio on account of both cost and dimensions; it is necessary, therefore, to devise other means which, while tending to reduce the volume of fusible metal to the lowest possible point, will so facilitate the ready escape and condensation of the hot metallic gases as to render the operation of the fuse quiet and reliable under all conditions.

Consider more in detail what actually takes place when an enclosed fuse is blown on short-circuit. As the rush of current occurs, the metal is raised through its melting point to its boiling point and the current continues to flow through the fuse for a brief interval on the conducting vapor path of the volatilized metal. It is extremely important that the temperature of these gases should be lowered with the greatest possible rapidity to a point where their conducting power ceases to exist, in order to bring about a reduction in the time of operation of the fuse, which is of tremendous importance in reducing the internal pressures developed and in preventing explosion.

To emphasize this characteristic more forcibly, consider that the maximum running temperature of the porous filling would be slightly less than the melting point of the metal of the fuse link, say approximately 315 degrees cent., were zinc employed and the fuse running at its full load capacity. When a short-circuit occurs, the metal of the link is suddenly raised to a temperature of at least 1000 degrees cent. and as the pressure in the tube becomes greater this temperature is increased. The relatively low temperature of the filling, however, immediately tends to cool these hot gases and convert them from a conducting medium into an actual insulator. Therefore, the sooner we can bring the hot gases into contact with the filling, or conversely, the sooner we can bring all the filling into action as a condenser, the more rapid will be the extinction of the arc within the fuse and the rupture of the circuit.

These considerations show that as little metal as possible must be used in the link and, further, its surface must be so extended as to provide every facility for the hot gases to escape and so distribute the metal within the mass of the filling that each particle of it shall be brought promptly into action.

All these conditions are effectively met by employing what is known as the "multiple link" or one of its modifications. It is quite a simple matter to obtain an increased link area of 100 per cent or more by this method, which will permit a reduction of at least 18 per cent in the total volume of the metal necessary for a given capacity, according to the design.

Reference to Chart 1, giving an end-section through three types of fusible links, will illustrate how readily this may be accomplished. In Fig. 1 we have an end-section of the widest practical single-strip link which could be used in a given tube. In Fig. 2 is shown how the surface may be readily extended 100 per cent without occupying a greater width, and with a further advantage that the metal is more widely distributed within the filling, rendering this far more effective and rapid in its action. At the same time the metal is brought closer to the radiating surface, which will also affect the total amount of metal necessary for a given capacity of a fuse. In Fig. 3 we have another arrangement of the same link which would also be effective. The mathematical consideration of the effect of a change in position of the conductors within the enclosing casing is interesting.

Applying the equation given in *Watson's Physics* on the transference of heat, and bearing in mind that this applies more strictly to transference between parallel surfaces and where the flow takes place in parallel lines, one can work out an equation which, with a proper value of the factor D, representing the distance through which the heat is transmitted, bears out the author's hypothesis, thus:

Chart No. 1.

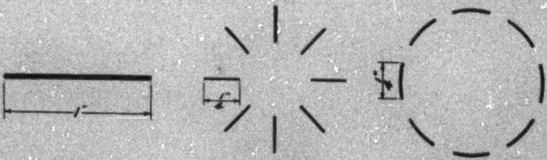


Fig. 1. Fig. 2. Fig. 3.

Length 3 inches
Area Fig. 1 = 6 sq. in.
Area Fig. 2 = 12 sq. in.
Area Fig. 3 = 12 sq. in.

$$Q = \frac{K A \, (T_2 - T_1) \, t}{d} \tag{1}$$

Where Q = the quantity of heat in calories,

K = a constant for any one substance which is independent of the thickness, area, or the difference in temperature, but changes with the substance used. In this case it refers to the porous filling and the tube,

d = the distance through which the heat is transmitted,

t = the time in seconds in which a given number of heat units would pass from one surface to the other.

T_1 and T_2 are the temperatures respectively of the two surfaces between which occurs the transmission of heat, in this case the temperature of the fuse casing at the surface and the temperature of the fuse link,

A = the area or average cross-section through which the heat passes. Transposing, we get the equation:

$$\frac{Q}{t} = \frac{K\,A\,(T_2 - T_1)}{d} \tag{2}$$

and representing the calories per second, Q/T by Q', the equation becomes:

$$Q' = \frac{K\,A\,(T_2 - T_1)}{d}. \tag{3}$$

It is desirable to transform this equation into electrical units.
One calorie per sec. = 4.189×10^7 ergs per sec.
10^7 ergs per sec. = 1 watt.
Therefore, 1 cal. per sec. = 4.189 watts.
From this it follows that

$$Q' = \frac{I^2 R}{4.189} \tag{4}$$

Substituting this equivalent in equation (3)

$$\frac{I^2R}{4.189} = \frac{K\,A\,(T_2 - T_1)}{d}, \tag{5}$$

in which I^2R = the total watt loss in the fuse.

Now, transposing and reducing to simpler form

$$I = 2.045 \sqrt{\frac{K}{R}\;\frac{A\,(T_2 - T_1)}{d}} \tag{6}$$

Since K and R are both constant for any given filling and fuse, we may represent $\sqrt{\frac{K}{R}}$ by K' and reduce the formula to a simpler form,

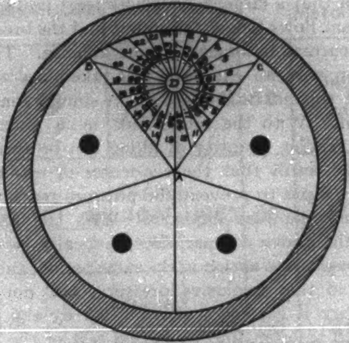
$$I = 2.045\,K' \sqrt{\frac{A\,(T_2 - T_1)}{d}} \tag{7}$$

As already pointed out, the value *d* must be determined in each case to meet the condition of divergent heat rays; but once determined, an examination of this equation shows that any variation in this factor, that is to say, any change in the position of the link, affects the current flow. This is further proved by tests of the fuses themselves which will be described later.

It will be apparent that in order to get the most satisfactory operation of an enclosed fuse, and one of the smallest possible dimensions for a given capacity, all the porous filling should be brought into service when the fuse is subjected to an excessive overload or short-circuit.

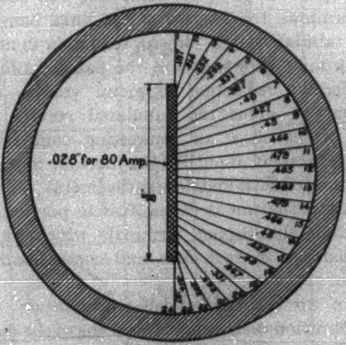
From this it is clear that the shorter the distance the gases have to pass in order to bring into action the maximum amount of filling, the greater will be the rapidity of condensation of the gases and the quicker will the arc be interrupted. To show what an important bearing a proper subdivision and distribution of the metal of the link has in accomplishing this result, consider the fuse sections shown in Chart 2, where in Fig. 1 we have a diagrammatic section through the center of a five-wire multiple fuse drawn three times larger than its actual dimensions. This is divided accurately into five segments, each segment, representing the space which must handle the gases evolved from one element of the link. The circle in the centre of each space represents accurately the proportionate diameter of the wire for a certain capacity of fuse and its relation to the enclosing space. The lines numbered from 1 to 24 represent the mean path or distance that the vapors have to travel in that specific direction in order to bring into action the total amount of filling. It will be understood that in actual practice the number of lines or paths would be materially greater, but for the present discussion any number which would divide the enclosing space into reasonably even proportions will be sufficient. The length of these lines has been accurately measured and their average length ascertained and found to be, as given in the diagram, 0.192 of an inch in the actual fuse, or in the diagram three times that length. In Chart 2, Fig. 2 we have a similar diagram of a flat-strip link of the same capacity. The space through which the gases will have to pass has been divided into an equal number with those of the multiple link and their average length determined. In this case the average length is found to be 0.363 of an inch, or with the flat

Chart No. 2.



Average length of vapor path=.192"

Fig. 1.


.028" for 80 Amp.
.307
.331
.367
.40
.427
.45
.466
.479
.485
.475
.466
.45
.427
.40
.367
.331
.307

Average length of vapor path=.363"

Fig. 2.

link the gases have to pass through an average distance 89 per cent greater than in the five-wire multiple link. In other words, the time which must elapse before all the filling can be brought into action to condense the vapor is nearly double, with the result that a larger amount of energy is absorbed by the fuse, the current flows longer through it and the breaking or rupturing of the current becomes far more difficult. This furnishes another reason why an explosion will take place with a single-strip link and will not take place under similar conditions with a multiple link. With the single link in a given period of time a much smaller quantity of filling can be reached by the gases, with the result that the condenser or cooling action is not sufficiently rapid to prevent the pressure reaching a disruptive point, and the fuse explodes. With the multiple link, according to the above comparison, practically twice the mass of filling is brought into action in the same period, and the cooling rate is so rapid that explosive pressures are not developed. That this theory is correct is shown both by the oscillograph records referred to later, and by actual test of the fuses themselves.

To ascertain definitely the actual reduction in metal volume for any given capacity of fuse, obtained by proper subdivision of the link, an extended series of calibration tests were made on a set of fuses under identically the same conditions. These fuses were all made up in tubes of the same size and fitted with the same size of terminal, the lengths of the links being the same. Chart 3 gives tabulated data for the reduction in metal secured with both the round wire link and the flat strip link, showing clearly the effective reduction in metal volume obtained in this way. Chart 4 gives the tabulated results of another series of tests which show an interesting comparison of the gain in capacity brought about by the increase in surface of the links and the proper distribution of the metal. The areas referred to are the actual areas of the fusible portion of the link and do not include the copper terminals which, as previously stated, were identical in each fuse and consequently could be disregarded.

Having taken up the theoretical consideration of the subject and the calibration tests supporting some of the deductions, it is desirable now to consider the actual operation of the fuse under short-circuit. To permit of a full consideration of the phenomena shown at various intervals during the blowing of the

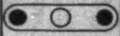
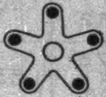
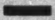
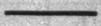
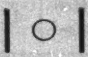
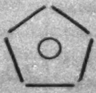
No. of Fuse	Style of Link.	Fuse Link Construction	Size of Link.	Volume Ratio	Ampères	Reduction in Metal Volume.
83	Single Wire		Diam. .164"	1.344%	80	Unit for Wire Links
106	2 Wire Multiple		Diam. .108" Each.	1.166%	80	13.22%
80	5 Wire Multiple		Diam. .063" Each.	.9919%	80	26.2%
88	Single Flat Strip		.063" x .3125"	1.253%	80	Unit for Strip Links.
86	Single Flat Strip		.028" x .625"	1.114%	80	11.1%
104	2 Strip Multiple		.0258" x .3125" Each	1.026%	80	18.1% Under No.88. 7.8% Under No.86.
105	5 Strip Multiple		.0095" x .3125" Each	.9447%	80	24.6% Under No.88 15.2% Under No.86

Chart 3

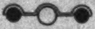
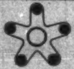
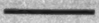
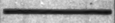
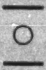
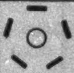
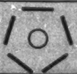
No. of Fuse.	Style of Link.	Fuse Link Construction.	Size of Link.	Area	Ampere Capacity
81	Single Wire.		Diam. .141"	1.33	60
96	2 Wire Multiple		Diam. .10"	1.88	73
80	5 Wire Multiple.		Diam. .063"	2.96	80
91	Single Flat Strip.		.100" x .1562"	1.537	65
90	Single Flat Strip.		.075" x .208"	1.856	67
87	Single Flat Strip.		.050" x .3125"	2.175	70
85	Single Flat Strip.		.025" x .625"	3.90	75
89	Single Flat Strip.		.0215" x .728"	4.50	75
97	2 Strip Multiple		.025" Thick .3125" Wide.	4.05	78
84	5 Strip Multiple		.025" Thick .125" Wide.	4.50	80
98	5 Strip Multiple		.0125" Thick. .25" Wide.	7.875	83

Chart 4

fuse under those conditions, an oscillograph was used. The resultant curves are given in Figs. 5 to 16, and the actual records of the tests, together with a drawing of an end-section of the links used in each case, with other important data relating to the test, are given in Chart 5. The tests consisted in subjecting fuses, similar in every detail of construction, except as relates to the fusible portion of the link, to direct short-circuit across the bus-bars of a 6000-ampere-hour battery fed by one or more 500-kw. generators. The potential coil of the oscillograph was connected across the fuse rather than across the circuit, in order to show clearly the variations in the volts' drop at different intervals. An examination of these several curves gives a most interesting and instructive history of the complete cycle of events occurring within the fuse during its operation, all within a period of time considerably under 0.05 seconds.

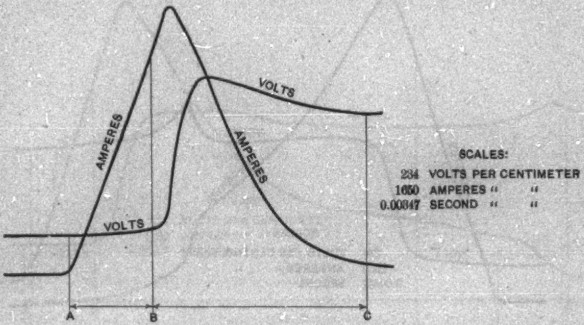


FIG. 5.—Five-wire multiple link 0.063 diam. capacity; 80 amperes. vol. ratio = 1 per cent

Referring to curve of Test IX, Fig. 12, as a good illustration, this may be analyzed as follows: This curve exhibits the operation of a five-strip multiple link fuse of 1 per cent volume ratio, 80 amperes capacity. Following the current curve, it will be seen that during the period *J A* the current is zero. At the instant *A*, the switch was closed and the current instantly rushed through the fuse, rapidly increasing in value until at *D* it had reached its maximum. It then begins to die away until at *C* it has become zero again, or in other words, the fuse has opened the circuit. Referring to the voltage curve from *K* to *Y*, the voltage as measured across the fuse is practically zero, that is to say, it was zero at *K* but at the beginning of the current flow, there was of course, a slight rise. This is, however, so small as not to be visible on the curve and for all practical purposes the voltage may be regarded during the interval *K Y* as zero. At the instant *Y*, the voltage begins to go up with great rapidity until it practically reaches its maximum at *I*; it then continues at almost even value until just before the rupture of the current, occurring at *C*, a slight inductive kick is noticed at *F*, after which it sharply declines and becomes constant at *M*, *M O* being the full voltage of the circuit across the fuse.

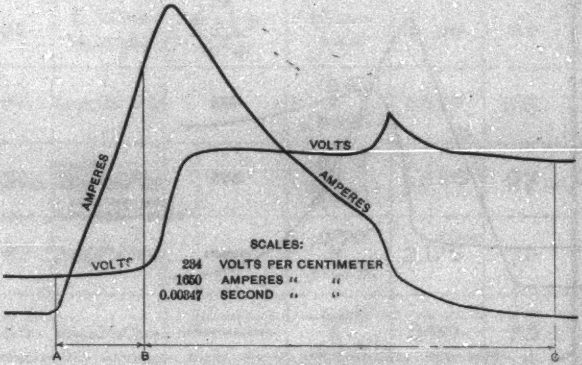


Fig. 6.—Single flat strip 0.028 x 0.625 wide. Capacity 80 amperes; vol. ratio = 1.12 per cent

Referring to the current curve, note the rapid rise of the current value from the point *A* to *E*. During that period, there was practically no voltage across the fuse. The actual time during which this rise in current was occurring, represented by the distance *A B*, is 0.0038 sec. It is during this interval that the fuse link is being raised to its melting point, the total energy impressed on the fuse being extremely small. From the point *E* on the current curve to its maximum value at *D*, the metal is being converted into vapor, and a corresponding rapid rise in voltage will be noted, showing the enormous increase in the resistance of the circuit. At *D*, the vapor begins to condense, or, in other words, lose its conductivity, and as the conductivity of the vapor path diminishes, the current falls. The voltage, however, continues to rise slightly, due to the same cause, but remains practically constant from the point *I* until just before reaching the point *F*. During this period the current is falling rapidly, and the total time or duration of fall is found to be 0.012 seconds. The maximum current which passes through the fuse is found to be 8415 amperes and the voltage at the same instant, found by measuring the height *H L*, was 304 volts, so that the power input into the fuse at the instant *G* is 2,558,160 watts, apparently an enormous amount of energy, but practically an instantaneous value. By integrating it is found that the average watts were 1,925,000 during the period that power was absorbed by the fuse. This period of energy input, is represented by the distance *B C*, and is found to be actually 0.0146 sec. from which is derived a value of 28,600 watt-sec. or a little over 27 B.t.u. The total period of operation, or the time *A C*, which elapsed after the switch was closed, until the circuit was opened, was but 0.0184 sec.

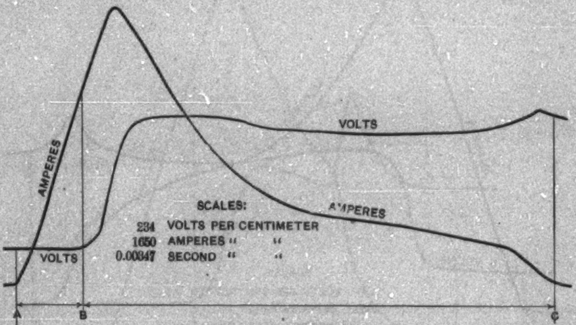


FIG. 7.—Single flat strip 0.050 x 0.3125 wide. Capacity 70 amperes; vol. ratio = 1 per cent

Referring to the curve, Test X, that of a single flat strip link fuse, it is noted that the time during which the link was being melted as represented by the distance *A B*, was practically the same as that of Curve IX of the previous test, but the significant feature lies in the relatively slow decline of the current value and the prolongation of the period during which energy was being absorbed by the fuse or the period *B C*. This time is actually 0.0246 sec. or an increase of 68 per cent in the period of operation of the fuse during which arcing was going on. By integrating the curve in precisely the same manner as that of Test IX, the average watts were found to be 2,360,000 and this value multiplied by the time, gives 58,000 watt-secs. or 57 B.t.u., an increase of the total energy input in excess of 102 per cent or more than double the total energy absorbed by the multiple strip fuse.

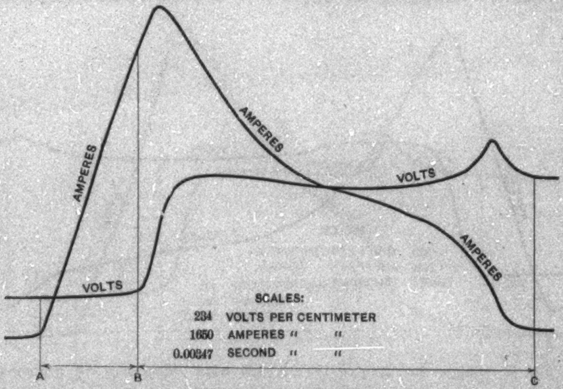


Fig. 8.—Single flat strip 0.030 x 0.625 wide. Capacity 83 amperes; vol. ratio = 1.19 per cent

A similar comparison of the other curves bears out in a most striking manner the important influence which the extension of the link surface and its proper distribution within the filling has in reducing to a large degree the total energy absorbed as well as the duration of the period of energy input. Comparing the results it will be found that the single link fuses invariably absorb more total energy.

The average energy input of the multiple link fuses tested was but 22,587 watt-secs. as compared with an average energy input of the single link fuses of 43,746 watt-secs.; that is to say, the single link fuses absorb practically double the energy. It should be further noted that even disregarding the fact that in several of the single link fuses, the explosion of the fuse materially shortened the period of power input, the average period of power input of the single link fuses was 72 per cent greater than the same period for the multiple link fuses.

Furthermore, in anything like equal ampere capacity the maximum current flow was greater with the single link fuses, the average excess being 15 per cent. This has an important bearing on the tendency to disrupt or burst the cartridge, since the greater the current, the more rapidly is the link raised to its boiling point and consequently the greater the rate of development of internal pressures. In all enclosed fuses provision is made for the escape of these gases. It will be apparent, therefore, that the rate of development of the gas must be considered, since in one case the rate of escape might be such as to prevent the ultimate bursting pressure being reached, whereas in another fuse of exactly the same metal volume, the rate of development of pressure might be so much more rapid than

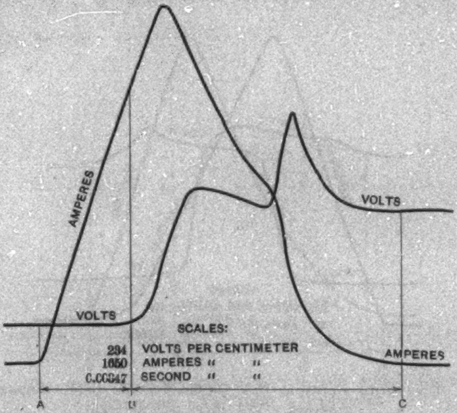


Fig. 9.—Single round wire 0.164 diam. Capacity 80 amperes. Vol. ratio = 1.35 per cent

its rate of escape that the bursting pressure would be rapidly reached.

I would briefly summarize the results of the other tests as shown in tabulated form in Chart 5 and the analyses of the other curves may be briefly summarized as follows:

Tests 1 and II (Figs. 5 and 6) compare the operation of a five-wire multiple link fuse and a single-strip flat link fuse of the same ampere capacity. By reference to Chart 5 it will be seen that the operation of the single flat link fuse was explosive and dangerous, whereas the multiple link fuse operated quietly. Comparison of these curves confirms this most forcibly. It will be noted that the period *A B*, during which the metal was being raised to its melting point, was practically the same for both fuses, but the period *B C*, during which energy was being absorbed by the fuse, was extended in a most pronounced manner in the single link and that the total energy absorbed was about 120 per cent greater.

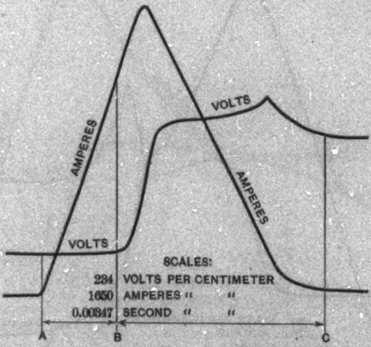


FIG. 10.—Five-strip, multiple link 0.0125 x 0.250 wide. Capacity 83 amperes. Vol. ratio = 1 per cent

Test III (Fig. 7) showing the operation of a single flat strip fuse of the same volume ratio as Test I but of a smaller ampere capacity, exhibits an extension of the period of energy input *B C* even in a more pronounced manner. The total energy absorbed in this fuse was nearly 140 per cent greater than with the multiple link.

In Tests IV and V (Fig. 8) we compare the operation of the five-strip multiple link fuse and the single-strip link of the same ampere capacity with the five-wire multiple link of the earlier test. Unfortunately the film record of Test IV was torn so that it was impossible to compare the curves. The record shows, however, that the multiple strip operated quietly, while the single strip exploded and one may judge of the characteristics of the curve of the multiple strip by reference to Test VII (Fig. 10) which was the curve made from a fuse of identically the same construction. The same characteristics are here presented as in Test I.

In Test VI (Fig. 9) is shown the operation of a single wire link fuse. This curve is particularly interesting as showing the effect of concentrating a mass of metal in as compact form as possible, thereby reducing to a minimum the avenues of escape of the gases within the filling. The rise of the current wave is more pronounced than in any of the other single link fuses, the current here reaching a maximum of 10,642 amperes; while the period of energy input, *B C*, is relatively short. This is due to the fact that this fuse exploded with greatest violence and the current was actually ruptured by the explosion. This is indicated by the very pronounced inductive kick shown on the curve, the rise in potential at the instant of rupture being about 450 volts.

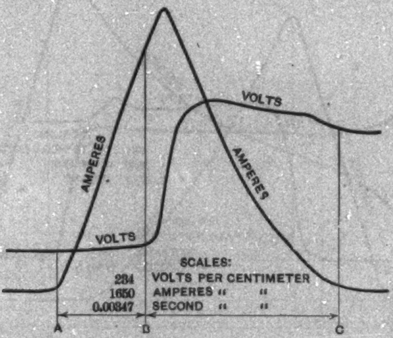


Fig. 11.—Two-strip multiple link 0.025 x 0.3125 wide. Capacity 78 amperes. Vol. ratio = 1 per cent

In Test VIII (Fig. 11) is shown the operation of a two-strip multiple link of slightly less capacity than that used in Test VII, its operation being most satisfactory in every way.

Tests IX, X and XI (Figs. 12, 13 and 14) give the comparative operation of two single-link fuses and a five-strip multiple link at 600 volts, as distinguished from 500 volts heretofore used. Again the multiple link operated quietly, whereas the two single-link fuses exploded.

Test XIII (Fig. 15) records the behavior of the curve of a fuse, where the explosion did not interrupt the current promptly but where the arc was maintained for a brief interval. The variations in the voltage during the period of arcing are here most pronounced.

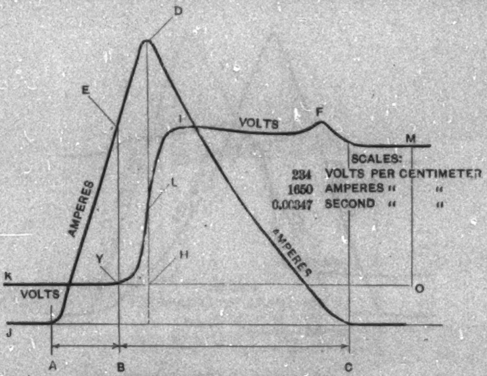


FIG. 12.—Five-strip multiple link 0.025 x 0.125 wide. Capacity 80 amperes. Vol. ratio = 1 per cent

In Test XV (Fig. 16) is shown the operation of a five-strip multiple link with a slight inductive resistance in the circuit. In comparison with other multiple link curves, the prolongation of the period *A B* is most marked with slower and less abrupt rise of the potential. The fuse operated perfectly although giving indications of the phenomena shown.

Another important consideration is the concentration of the energy at one point in a single-strip fuse as compared with its division in the multiple-link fuse. An interesting illustration of this particular feature is found in Tests I and II. The fuse of Test I was a five-wire multiple link, the total resistance of which was 0.0017 ohms or the resistance of each element was 0.0085 ohms. The maximum current flow through this fuse, the record shows was 7600 amperes, from which it is obvious that the energy required for raising the metal to the boiling point of each element was 19,650 watts or a total for the fuse of 98,250 watts. Compared with the single-strip link of Test II, the resistance of which was somewhat lower on account of its greater volume ratio, being 0.0015 ohms, the maximum current flow was seen to be 8910 amperes, giving a total power input of 123,700 watts. In other words, 25,000 more watts were absorbed by the single link fuse at the period of maximum current flow than by the multiple link, and further than that all of this energy was developed at one plane at the center of the fuse, whereas with the multiple link but 19,650 watts was developed in each element; that is to say, there was over six times as much energy developed at one point of the single link fuse as in the multiple link.

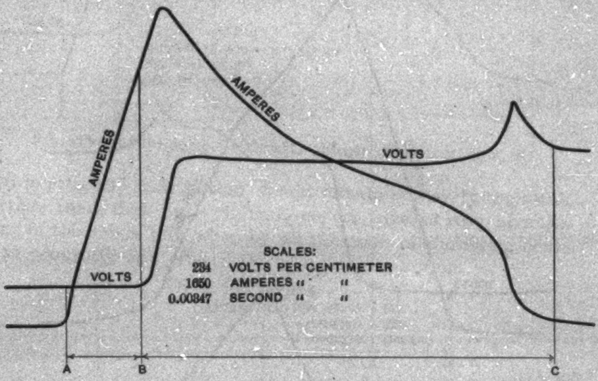


Fig. 13.—Single flat strip 0.028 x 0.625 wide. Capacity 80 amperes. Vol. ratio = 1.12 per cent

Now under such conditions it must be realized that there exists in the flat link fuse a hole or tunnel through the filling, being the space formerly occupied by the metal of the link, which is momentarily filled with a conducting vapor. The conductivity of this vapor is dependent very largely upon its density. In this concentration of a relatively large amount of vapor within an extremely confined space, and consequently of relatively great density, is found one explanation for the greater current flow seen in every instance in the single-strip link. With the multiple-link fuse we have five tunnels distributed at wide intervals within the tubing, the energy in each one being but one-sixth that in the single tunnel of the other fuse. Moreover, it has been shown that with the single link fuse, the vapor has to travel approximately twice the distance in order to bring all the filling into action as a condenser, and consequently requires more time than with the multiple fuse. Therefore, with the single link fuse, there is a rapid accumulation of pressure and a pronouncedly greater current flow, or an accumulative effect resulting in the disruptive action noted.

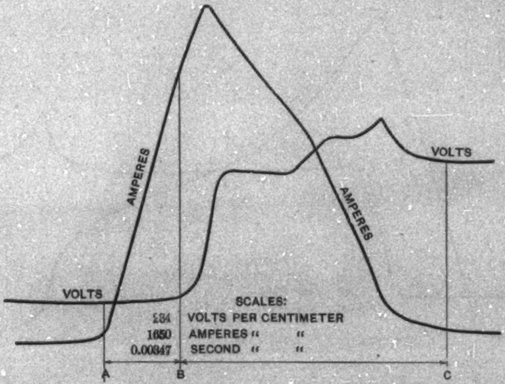


Fig. 14.—Single flat strip 0.063 x 0.3125 wide. Capacity 80 amperes. Vol. ratio = 1.26 per cent

The statement may be made that in making these comparative tests possibly the most efficient form of single link fuse is not used, and that the area might be extended by using a greater width and folding up the edges, etc. In this connection it should be pointed out that such modifications could hardly affect the results, since if such a peculiar form of single link fuse were employed, the same form could, of course, be used in the elements of the multiple strip for comparison, and the gain, both in area and distribution, would remain relatively the same. Further than that, it is difficult to conceive of any arrangement of the single link whereby all the mass of the filling could be so promptly and effectively brought into action.

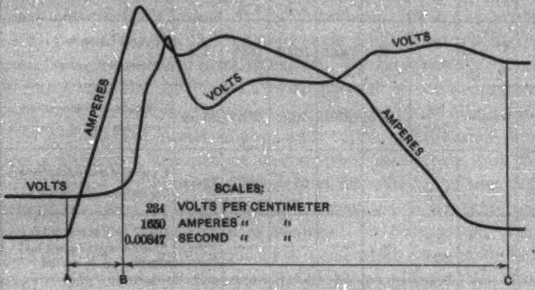


FIG. 15.—60 amperes, 600-volt. Single flat-strip link

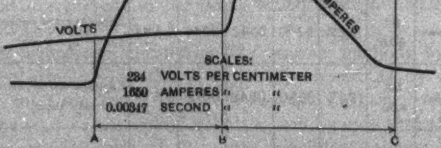
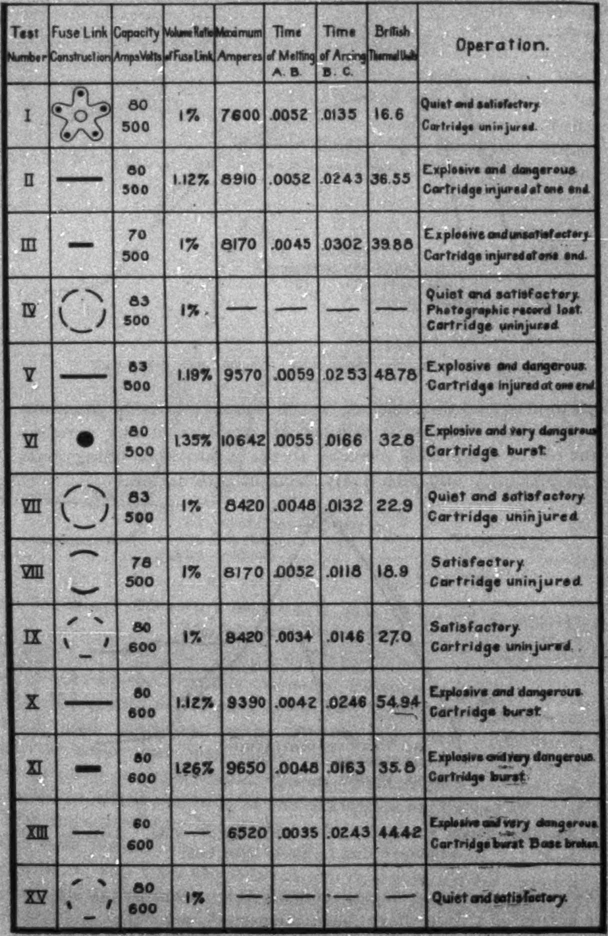


FIG. 16.—Five-strip multiple link 0.025 x 0.125 wide. Capacity 80 amperes. Vol. ratio = 1 per cent

Two other possible causes contributing towards the explosive action of a fuse have been suggested, one, the presence within the filling of a certain percentage of moisture and within the casing of a certain amount of air which, it was claimed, was



Test Number	Fuse Link Construction	Capacity Amps Volts	Volume Ratio of Fuse Link	Maximum Amperes	Time of Melting A. B.	Time of Arcing B. C.	British Thermal Units	Operation.
I		80 500	1%	7600	.0052	.0135	16.6	Quiet and satisfactory. Cartridge uninjured.
II	—	80 500	1.12%	8910	.0052	.0243	36.55	Explosive and dangerous. Cartridge injured at one end.
III	▬	70 500	1%	8170	.0045	.0302	39.88	Explosive and unsatisfactory. Cartridge injured at one end.
IV		83 500	1%.	—	—	—	—	Quiet and satisfactory. Photographic record lost. Cartridge uninjured.
V	—	83 500	1.19%	9570	.0059	.0253	48.78	Explosive and dangerous. Cartridge injured at one end.
VI	●	80 500	1.35%	10642	.0055	.0166	32.8	Explosive and very dangerous. Cartridge burst.
VII		83 500	1%	8420	.0048	.0132	22.9	Quiet and satisfactory. Cartridge uninjured.
VIII		78 500	1%	8170	.0052	.0118	18.9	Satisfactory. Cartridge uninjured.
IX		80 600	1%	8420	.0034	.0146	27.0	Satisfactory. Cartridge uninjured.
X	—	80 600	1.12%	9390	.0042	.0246	54.94	Explosive and dangerous. Cartridge burst.
XI	▬	80 600	1.26%	9650	.0048	.0163	35.8	Explosive and very dangerous. Cartridge burst.
XIII	—	60 600	—	6520	.0035	.0243	44.42	Explosive and very dangerous. Cartridge burst. Base broken.
XV		80 600	1%	—	—	—	—	Quiet and satisfactory.

Chart 5.

suddenly and rapidly expanded by the heat of the arc. An examination of the filling of the ordinary fuse will show that there can be no material amount of air, the heating of which would occasion the violent explosions resulting from short-circuit, particularly when it is considered that the metal generally used for the link expands over 2400 times when converted from its metallic form to vapor. By actual measurement it is found that the total volume of air present in the average enclosed fuse is in the neighborhood of 19 per cent of the filling used.

The presence of water might cause serious disturbance were there a sufficient amount of it converted into steam, but this would require the heating of the entire mass of filling to a high temperature; and to raise it to this temperature in the extremely short interval of time which is required to operate the fuse, would call for the application of a tremendous amount of heat energy. Of course if the arc should be maintained, the filling would rapidly reach such a temperature, but the condition under consideration is one where the fuse explodes when it is short-circuited, and as there can be no prolonged maintenance of the arc under this explosive action, which would affect the filling, it could not be heated in that manner and the only heat which could be applied for that particular purpose is that absorbed by the fuse in converting the metal of the link into its vapor. Actual measurement was made of the percentage of moisture present in the filling, both before and after a fuse had been subjected to a severe short-circuit which it had handled satisfactorily. Starting with an initial amount of 5 per cent, nearly 3 per cent remained, showing that but a little over 2 per cent of the total moisture had been driven off; namely, that portion of the moisture present in the filling which was quite close to the metal of the link.

While there are unquestionably various methods by which relatively the same effects may be produced as by the use of the multiple link, such, for example, as the well-known cigarette fuse or the cylinder link, it will be seen that these are but the amplification of the same principles; namely, extreme extension of surface and such an arrangement of the metal that the greatest possible contact with the filling is provided, to increase to the greatest degree the avenues of escape of the gases.

DISCUSSION ON "SOME CONSIDERATIONS IN DESIGNING HEAVY CAPACITY FUSES." FRONTENAC, N. Y., JUNE 30, 1909

Louis W. Downes: In making these investigations, the conditions on heavy overload and on short-circuits were principally considered. The analyses of the curves show to what a remarkably uniform degree they sustain the theory of proper fuse design, as I believe it is given in the paper. I would ask your special attention to the summary of the curves given in Fig. 8, and particularly to a comparison of tests 9 and 10, Figs. 12 and 13.

C. Francis Harding: In this and other papers presented before this convention, it is interesting to note the use of the oscillograph in studying electric phenomena under widely varying conditions. Several years ago when I made tests of enclosed fuses, the oscillograph had not been introduced for this purpose. It was attempted to determine the energy taken by the fuse under full-load, overload, and short-circuit conditions by measuring the resistance of the link and calculating the energy as I^2R loss. It was thought that a considerable discrepancy might exist in this method because the resistance was taken across the link alone, while there might also be a fairly high resistance in the joint between the link and the blade. There was, of course, resistance in the blade itself which caused heating. It was difficult, therefore, to determine just the amount of energy used in the fuse link itself—energy which must be carried by conduction to the tube and later radiated to the air.

Mr. Downes states that he has used and still uses that method in addition to the oscillograph method, and has calculated the energy taken by the fuse from the measurements of resistance as well as from the product of volts and amperes taken from the oscillograph. However, he has not compared these two methods of determining the energy. It would be interesting to determine how much of this heating comes from the soldered joint, how much from portions of the blades and how much from the link. As I understand it, the oscillograph product of volts by amperes would give the total energy expended in the fuse.

It is stated in the paper that the advantage of the multiple link over the single link is principally due to the shortening of the path through which the heated gases must be conducted to the tube, and also to the increase of surface area of the link. The fuses are identical as far as the blades are concerned, but I do not understand that the supports of the links are the same. I wish to ask how much of this difference between the action of the multiple link and that of the single link may be due to the conduction of heat away from the link, owing to the difference in the support, the multiple link having a much heavier support than the single link?

I would also like to know what effect a change in filling would have with the single link. I take it that the filling is the same in all cases. With the single link a larger amount of gas is generated in a small space than with the multiple link, and it would seem that if the voids in the filling were greater with the single link than with the multiple link there might be a freer path for the gases to reach the blow-holes, and possibly better operation of the single link in that case.

In the last paragraph of the paper the question of moisture in the filling is taken up, and it is also stated that the fuses were tested directly on short-circuit, without apparently anything being said about full-load or part-load operation. It seems to me that this condition is a bit different from that to which the fuses would be subjected in practice. Ordinarily the short-circuiting occurs with the circuit previously closed; that is, the fuses are under heavy load, three-quarters, or perhaps full load when the short-circuiting takes place. If the moisture—3 to 5 per cent in these fuses—be dissipated by the heat before this short-circuiting takes place, and held somewhere in the fuse ready to produce energy in the form of steam when the short-circuit occurs, this condition is different from that in the tests. As is well known, most of the fillers used in fuses are more or less hydroscopic, and the amount of the moisture in the filler will probably vary with the weather conditions and with the particular atmosphere in which the fuses are operated.

J. C. Lincoln: I wish to enquire as to the accuracy of these enclosed fuses. For instance, working at nearly full load, are the fuses accurate within 10 per cent or 20 per cent, or about what is the limit of accuracy which they may be expected to show? Secondly, is the fuse material itself of such a nature that when the fuse blows the gases will have the effect of blowing out the arc? I understand that some of the metals, in which zinc is one of the components, have this property to some extent. Is anything of this nature used in the fuse link itself?

W. S. Andrews: The paper shows the wonderful development of the art since the time, now nearly thirty years ago, when by mere chance I was called upon by Mr. Edison to make the first fusible links that were ever used for the protection of incandescent lamp circuits. Most of the fuses used in those early days were open, but a patent was allowed to Mr. Edison in 1880 for an enclosed fuse. It was customary to clamp the bare fuse wire under a screw-head, and this naturally made poor contact. To correct this, the late Luther Stieringer invented what he termed a "hard end fuse," which, as is well known, consisted of a fuse strip with copper ends. This improvement constituted the first important step toward the production of a reliable fuse link. A patent on this improved safety fuse was allowed to Mr. Stieringer in 1886.

A. E. Kennelly: The oscillograms in the paper are of great interest and value because they indicate the electrical actions that may occur when a large storage-battery is suddenly placed on a heavy short-circuit close to the switchboard, and also how severe are the duties of an enclosed fuse in such cases.

It will be seen that the current starts to increase at the rate of some 2,000,000 amperes per second. If the fuse does not suppress the enclosed arc in the first 0.01 sec. or so, the energy liberated within the fuse itself will be enormous.

Even when the fuse performs its functions promptly and satisfactorily, the quantity of energy liberated within it is about the same as in the cartridge of an ordinary shot-gun when fired.

Moreover, it is desirable that the rate of throttling of the current should be fairly uniform, otherwise there will be a considerable rise of voltage induced in the circuit by $L \frac{dI}{dt}$.

Louis W. Downes: In replying to Mr. Harding's questions in regard to the variation in construction between the different fuses used in these tests, I will say that he is mistaken in his inference that there was a difference in the construction between the multiple-link and the single-link fuses tested. They were all exactly the same, particularly the terminal wires; these were of the same length and of the same cross-section. The only difference in construction is that shown in the method of supporting the fusible portion of the link. That is shown in Chart 3 and Chart 4. In the five-wire multiple link there is a small star-shaped stamping of hard metal through the center of which the terminal wire, shown by the circle, is carried and to which it is soldered, the terminal wire being identically the same in all fuses.

The spacing in the filling, within certain limitations, has little to do with the case beyond a certain point; namely, it permits the escape of the gases, but if the spacings are too large, so that there is too great a flow of gas through any one section, then trouble will be experienced.

I believe the oscillograph tests clearly sustain the theory that the chief function of the filling in the enclosed fuses is to act in the capacity of a condenser; in other words. the volatilized metal of the fuse-link possesses a relatively high conductivity while hot. Below a certain temperature that conductivity ceases to exist and the condensed gas actually becomes an insulator, or at least possesses high insulating properties. Consequently, if a very coarse filling were used, having of necessity wide spaces among the particles, the volume of gas rushing through these spaces at one or more points might affect the cooling action of the filling to such an extent that the temperature of the gases would not be brought to a sufficiently low point to destroy their electrical conductivity; hence the arc would be maintained by the passage of the current through such a vapor path. It is desirable, therefore, to have the filling broken up into as fine particles as possible so as to present the greatest possible condensing surface to the hot gas, bearing in mind at the same time that the degree of fineness must not be such as to interfere with the ready passage of the gases through the mass of the filling. From this it will be seen that it is desirable to avoid too large spaces among the particles of the filling, and so to arrange the elements of the link that every particle of filling can be brought into action in the shortest possible time. In that way alone can we prevent the maintenance of an arc within the fuse. If the arc is not interrupted explosions or disruptions of the casing will soon result.

Mr. Harding further referred to the presence of moisture in the filling, and asked if it were not a fact that in fuses under load the moisture would be largely driven out by the high temperature of the fuse-link within the casing. We have found by rather an extensive investigation that it is extremely difficult to drive out all the moisture contained in the average porous filling. I wish to say, incidentally, that every enclosed-fuse manufacturer to-day is using for filling purposes practically the same material; namely, the different salts of calcium—calcium carbonate and calcium sulphate particularly.

We find that a filling as it comes from the mixers, ordinarily will contain from 16 to 18 per cent of moisture, and it is necessary to raise it to a temperature of between 600 and 700 deg. fahr. to drive this moisture off to any extent. After the moisture is down to about 4 or 5 per cent it will remain practically a constant factor and does not seem to be affected materially by atmospheric conditions, as we have exposed filling to the atmosphere in very foggy weather and have found no appreciable increase in the percentage of moisture, provided it has first been brought down to 5 per cent.

I do not think that Mr. Harding is correct in stating that an enclosed fuse at full load would have all the moisture driven out, because there is only a very small part of the fuse which approaches the high temperature necessary to drive the moisture off; that is, the part immediately in contact with the metal of the link, which if of zinc would run approximately between 500 and 600 deg. The exterior casing, however, runs at a very much lower temperature, about 160 deg. to 165 deg. being approximately the limit. This temperature limit is fixed by the fact that continued operation of the fuse at 175 to 180 deg. will rapidly destroy the fibre tubing, which will then become very brittle and would be likely to explode should the fuse be subjected to a heavy short-circuit.

Mr. Harding also asked where these tests were made—more particularly the short-circuiting—and if they actually represented a practically operative condition. As a matter of fact, the investigations were made with the idea of determining accurately the best method of avoiding the most serious difficulty of enclosed fuses; that is, explosion of the casing. Manufacturers had been troubled from time to time by the terrific explosions of the enclosed fuses, which were dangerous not only to property but to life if a man happened to be near the fuse when it exploded. Those explosions occured in the commercial operation of the fuse, so I do not feel it can be said that we have imposed impossible conditions upon the fuse in these tests.

A large amount of energy is available at the switchboard of stations all over the country, and a fuse is frequently called upon to withstand direct short-circuits under the most severe conditions. As an illustration, in New York City the fuses on the elevated railway and in the subway, with the enormous generating stations back of them, are carried on the truck and are there relied upon to sustain practically direct short-circuits between the third rail and the structure. A fuse that will not withstand that test is not only of no value, but is also a considerable menace to the company; for if one of them should explode as a train is drawing into a station, the result would be disastrous to the company financially from resultant damage suits.

In regard to Mr. Lincoln's inquiry concerning the accuracy of the fuse and the nature of the fuse metal, I would say that the accuracy of the fuse of course depends very largely upon the care with which it is designed, but it is not difficult to make a fuse which is within 10 per cent of its ratings. The great difficulty in the enclosed fuse is the difference in the overload blowing time when a fuse is first put into the circuit and after it has been in the circuit for some time, due to the fact that the heat conductivity of the porous material which is immediately in contact with the metal of the link of course rapidly decreases as the temperature rises. That to a certain extent does affect the accuracy of the fuse, but not to an extent which renders its use impracticable. There are several methods of overcoming this defect, the most common being the notching of the link to bring about a high current density at the center; and the other, the use of the air drum. By confining a small body of air immediately about the central part of the link, the heat is less rapidly absorbed by the filling at that point. That fuse possesses an astonishingly high degree of accuracy whether cool or hot. Its characteristic curve will be found to run uniform and the blowing time at any given overload is constant.

Mr. Lincoln's other inquiry as to whether any metal was employed which possesses a tendency to blow out the arc, I have already referred to by stating that the filling was what destroyed the arc by condensing the conducting medium; namely, the metallic vapor at the time of the operation of the fuse. As far as I know, there is not any practical difference in the arcing effect of any of the softer metals, such as zinc, aluminum, lead, tin alloys, lead-bismuth alloys, or in combinations of these—all of which I have tried very extensively and in a great many different mixtures. The harder metals, copper and silver, owing to their higher boiling point, are not well adapted for use in fuses, particularly enclosed fuses. The higher melting point affects them and the conversion of the metal into its vapor is accompanied by a more explosive action. I doubt very much if any effective results would be produced by what Mr. Linclon referred to; that is, the so-called tendency of the gases of some of the metals to extinguish an arc.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

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COMPARATIVE COSTS OF 25-CYCLE AND 60-CYCLE ALTERNATORS

BY CARL J. FECHHEIMER

The statement is frequently made that 25-cycle alternators are more expensive than 60-cycle machines built for the same output, speed, voltage, and phase. A considerable difference of opinion exists at the present time as to how much more the low-frequency machine should cost than the corresponding high-frequency machine. When an attempt is made to analyze conditions, by examining the cost records of machines built by a large manufacturing company, one is confronted by a maze of figures which assist but little toward solving the problem. This is not at all surprising when one considers the many changes which have accompanied the rapid development of alternating-current generators. Some machines have a relatively great amount of iron, while others have a relatively great amount of copper; there is considerable difference in the results obtained from the various methods used for ventilating alternators; some are much more liberal as regards heating, or voltage margin, or regulation, than others; the excitation differs appreciably in machines for nearly the same rating; some were built when material and labor were high, etc. In this paper an attempt has been made to eliminate, as far as possible, some of these variables.

In a paper entitled "The Relative Proportions of Copper and Iron in Alternators," read by the writer before the Atlantic City Convention of the Institute in 1908, a method was worked out for determining the value of flux necessary to obtain the cheapest machine. In the appendix, which was subsequently added, the cost of the exciter is brought into the equations, with the view of reducing to a minimum the cost of the entire equipment, including alternator and exciter. In this paper the method employed has been to determine this value of flux for a machine of a given rating, and to use this value of flux for determining the capacity and cost of the exciter, the approximate diameter and length of machine, and the weights and costs of material in each of the principal parts of the alternator, in accordance with the method described in the paper referred to.

A sufficient number of points for plotting curves was worked out for two speeds common to 60-cycle and 25-cycle alternators; namely, 300 and 100 rev. per min. The former speed is intended to apply to water-wheel-driven alternators, and the latter to engine-type alternators. The curves are intended to apply to revolving-field alternators having rectangular poles.

They are further intended to apply to three-phase machines wound for approximately 2300 volts. The high-voltage machines require somewhat lower flux densities in the stator iron, and the necessity of using deeper slots in the stator causes the teeth to become a larger factor of the total stator iron than was allowed for. Moreover, the heating of the stator coils for the same copper loss is considerably greater than in the low-voltage machine. Furthermore, the insulation and the labor required for placing it on the coils become considerable factors in the cost of the alternator.

Allowances were made for each alternator to have an inherent regulation of about 8 and 19 per cent at normal load, and at unity and 85 per cent power-factor respectively; each will be capable of giving its normal voltage at 25 per cent overload in kilowatts at 85 per cent power-factor. The temperature rise of the stator coils will be about 35 degrees cent., when operated at full load for 24 hr., and 50 degrees when operated at 25 per cent overload for 2 hr. following the full-load run, these temperatures being based on 100 per cent power-factor conditions.

A curve was plotted with kilowatts per 100 rev. per min. against the cost of exciters; and from this curve the cost per kilowatt (*pe*) of the exciters could be determined. The exciters were considered to be belted units with a pulley ratio of 3 to 1. This represents about the average condition; for in a large number of plants the exciting current is taken directly from the direct-current bus-bars, in which case no exciter is furnished, while in others, an engine or motor-driven exciter is used.

In the following table, the values assumed for the various constants used are given.

TABLE I.

	100 rev. per min.		300 rev. per min.	
	25 cycles	60 cycles	25 cycles	60 cycles
B_a = Flux density in armature core in kilolines per sq. in.	65	40	68	40
$B_{f.r.}$ = Flux density in field ring in kilolines per sq. in.	38 (C.I.)	38 (C.I.)	70 (C.S.)	70 (C.S.)
B_p = Flux density in poles in kilolines per sq. in.	98	93	98	93
k = Distribution factor for stator coils	0.955	0.955	0.955	0.955
K = Ratio of net to gross iron in poles	0.91	0.91	0.91	0.91
K^{I} = Ratio of field ampere-turns per pole required for full field to the armature ampere conductors per pole with full load	1.7	1.8	1.7	1.8
K^{II} = Ratio of tangential dimension of pole to axial length of pole	0.5	0.34	0.65	0.45
K^{III} = Resistivity in micro-ohms, of an inch cube of copper at the temperature of the fields when hot	0.85	0.85	0.85	0.85
K^{IV} = Ratio of axial length of pole to pole pitch	1.	1.5	.75	1.
K^{VI} = Factor by which the product of amperes per sq. in. and ampere conductors per in. should be divided to give the temperature rise in degrees centigrade of armature coils	3.x10^4	3.5x10^4	3.5x10^4	4x10^4
K^{VII} = Ratio of length of armature end connection per coil to pole pitch	3.6	3.6	3.6	3.6
K^{IX} = Ratio of net iron in armature to axial length of pole	0.8	0.8	0.81	0.81
K^{XI} = Coefficient used for determining weight of yoke	1.9	1.9	2.2	1.9
K^{XIII} = Ratio of pole radial height to sq. root of pole tangential dimension	3.1	3.1	3.1	3.1
p_a = Price, in dollars per pound, of armature copper	0.2	0.2	0.2	0.2
p_{ai} = Price, in dollars per pound, of armature active iron	.0325	.0325	0.0325	.0325
p_f = Price, in dollars per pound, of field copper	0.2	0.2	0.2	0.2
$p_{f.r.}$ = Price, in dollars per pound, of field ring material	0.0225 to 0.025	0.0225 to 0.025	0.0325	0.0325
p_p = Price, in dollars per pound, of pole iron	0.0215	0.0215	0.0215	0.0215
p_y = Price, in dollars per pound, of yoke iron	0.0225 to 0.025	0.0225 to 0.025	0.0225 to 0.025	0.0225 to 0.025
T = Temperature rise in degrees centigrade, of armature coils	35	35	35	35
σ = Pole leakage factor	1.2	1.2	1.2	1.2
σ' = Field-ring leakage factor	1.25	1.25	1.25	1.25

The following additions were made for scrap material and parts not included in equations.

TABLE II.

	100 rev. per min.		300 rev. per min.	
	25 cycles	60 cycles	25 cycles	60 cycles
Field copper	2%	2%	2%	2%
Armature copper	10%	10%	10to12%	10to12%
Armature active iron	45%	50%	45to50%	50to60%
Yoke	15%	15%	15%	15%
Poles	25%	25%	25%	25%
Field ring	25%	25%	25%	25%

From an inspection of equation (21) in the paper previously referred to, it will be seen that if the same constants were employed, and the flux per pole varied inversely as the frequency, then the product of field copper weight and excitation would vary inversely as the frequency. The flux per pole is about three times as great in the 25-cycle as in the 60-cycle machine, and as there is a difference in the constants, the product is only about 44 per cent greater in the 25-cycle than in the 60-cycle machine. This is shown in Figs. 1 and 2.

As in the case of the field copper, if the constants were the same for the 25-cycle and 60-cycle alternators and if the flux per pole varied inversely with the frequency, the armature copper would vary inversely with the frequency. As will be seen from Fig. 2, however, the difference is but 63 per cent.

The necessity for using more active iron in the stator of the 25-cycle machine is evident, even though considerably higher densities are used, especially since the flux per pole is about three times as high in the 25-cycle as in the 60-cycle machine. The relative costs are shown in Fig. 3, where a difference of about 35 per cent appears.

The necessity for making the radial height of the pole greater in the 25-cycle than in the 60-cycle alternator, due to the greater number of ampere-turns, makes the weight of the poles for the former considerably greater than the latter. In Fig. 3 this difference will be seen to be about 70 per cent.

Since the internal diameter of the stator of the 25-cycle alternator is less than of the 60-cycle, the weight of the yoke will be very nearly the same, even though the axial length and radial depth of laminations are greater, and the greater depth of laminations necessitates a somewhat stiffer construction. This is shown in Fig. 4.

The field ring, while somewhat smaller in diameter for the 25-cycle machine, must be sufficiently greater in section to carry the greater flux per pole. For determining these curves, the assumption has been made that if the field ring is large enough to carry the flux, its cross-sectional area will be sufficient for mechanical purposes. The material used has been taken to be cast iron for the 100-rev. per min. machines, and cast steel for the 300-rev. per min. machines. From Fig. 4 it will be seen that the field ring is approximately twice as heavy for the 25-cycle as for the 60-cycle machine.

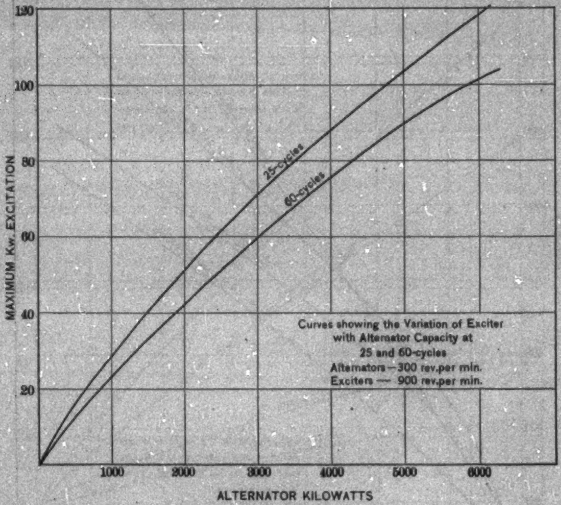
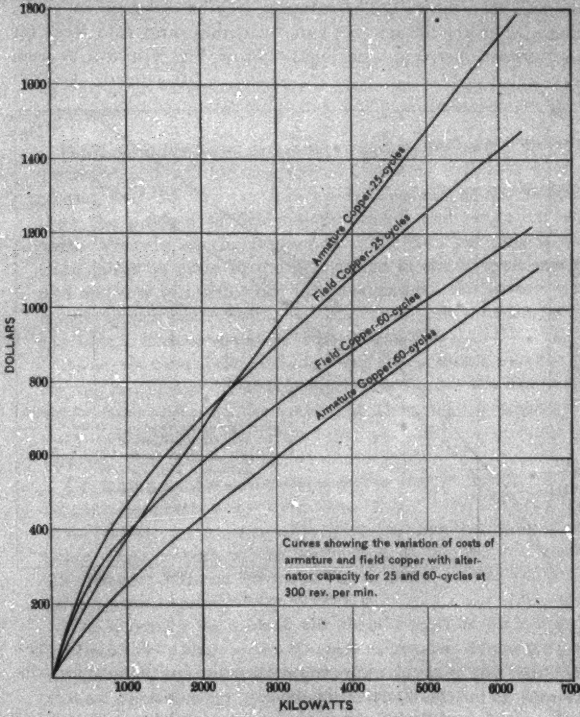


FIG. 1

Figs. 5, 6, and 7 show the comparative weights and costs of the copper and iron in the principal parts of the alternator. The principal parts include the armature and field copper, the armature active iron, the yoke, poles, and field ring.

With the exception of the curves shown in Fig. 7, the curves above described apply to alternators operating at 300 rev. per min. In Fig. 8, the relative costs of material in the principal parts are shown in the forms of curves for 25 and 60-cycle alternators operating at 100 and 300 rev. per min. It is interesting to note that the principal material in the 25-cycle machine at 300 rev. per min. will cost nearly as much



Curves showing the variation of costs of armature and field copper with alternator capacity for 25 and 60-cycles at 300 rev. per min.

FIG. 2

as the equivalent material in the 60-cycle at 100 rev. per min. Also the cost of the 25-cycle machine at 300 rev. per min. will be about 42 per cent more than of the 60-cycle machine, whereas the difference is but 33 per cent at 100 rev. per min. This condition exists, even though the "cubical contents" of the stator (represented by the product of the axial length of pole and the square of the internal diameter of the stator) is slightly less in the 25-cycle machine at 300 rev. per min., and slightly greater at 100 rev. per min., as shown in Fig. 9.

In order to determine the cost of the total material in the alternator, the cost of material in the principal parts was compared with the total cost of material in a number of alternators which had previously been built. In estimating the cost of material in the principal parts of these machines, about the same allowances were made for unavoidable scrap material as those given in Table II, and the prices of the materials were taken to be the same as existed at the time at which the various alternators were built. The ratings of each of the alternators were nearly the same as those for which the estimated curves in this paper are given. None of them was made with heavy rotors

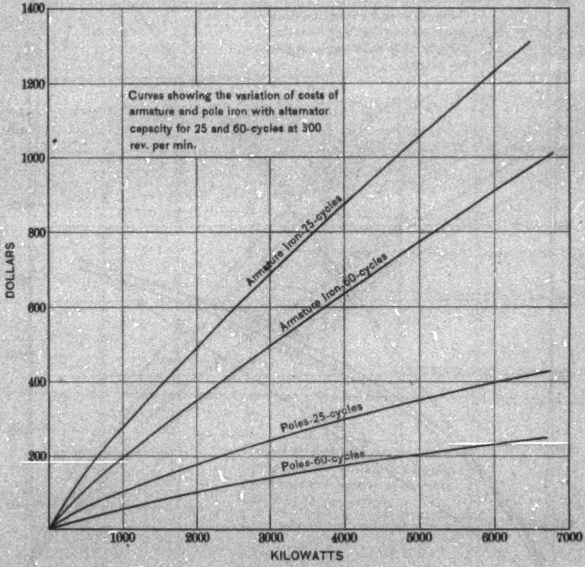


FIG. 3

with expensive material therein, necessitated by high overspeed requirements. The ratio of the cost of total material to material in the principal parts was found to lie between 1.4 and 2, the former applying as a lower limit to the engine type of alternator, and the latter as an upper limit to water-wheel type alternators.

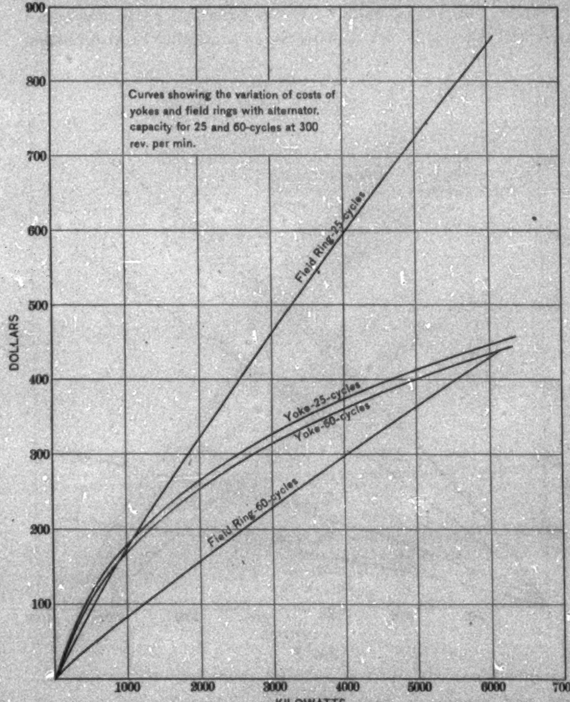


FIG. 4

For the purpose of determining the relation which the labor bears to material in the alternator, the ratio of labor to material was plotted against kilowatts per 100 rev. per min. for a large number of 60-cycle and 25-cycle engine and water-wheel-driven alternators which had previously been built. The burden has been omitted in allowing for the labor. Although this is contrary to the usual method of estimating costs, it has been taken to be nearly correct for an estimate of the character undertaken in this paper; for it is evident that the office expenses and other fixed charges usually included in the burden, are affected little, if any, by the frequency, or even by the size of machine which the factory undertakes to build.

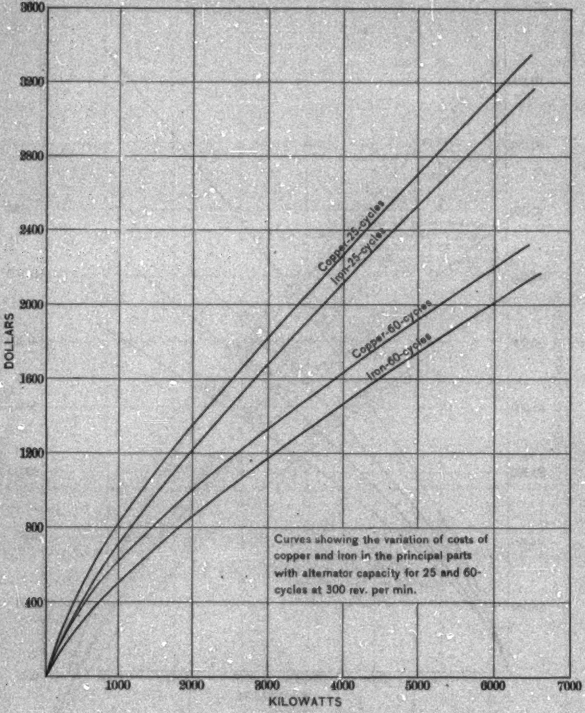
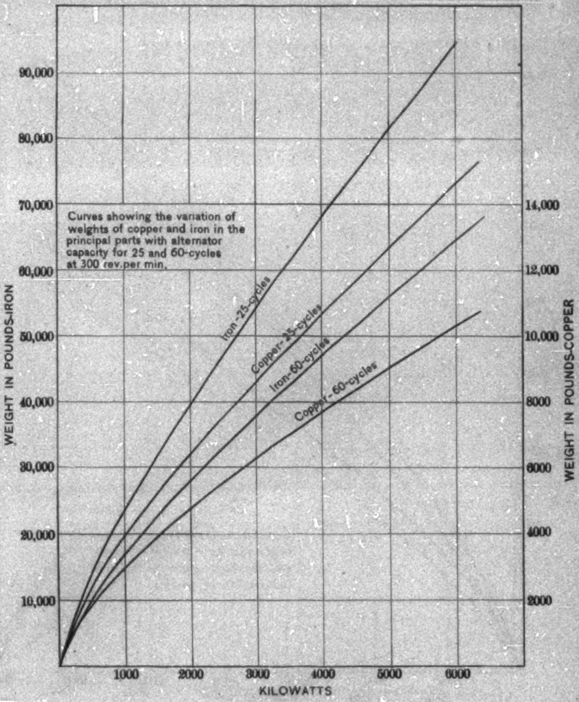


FIG. 5

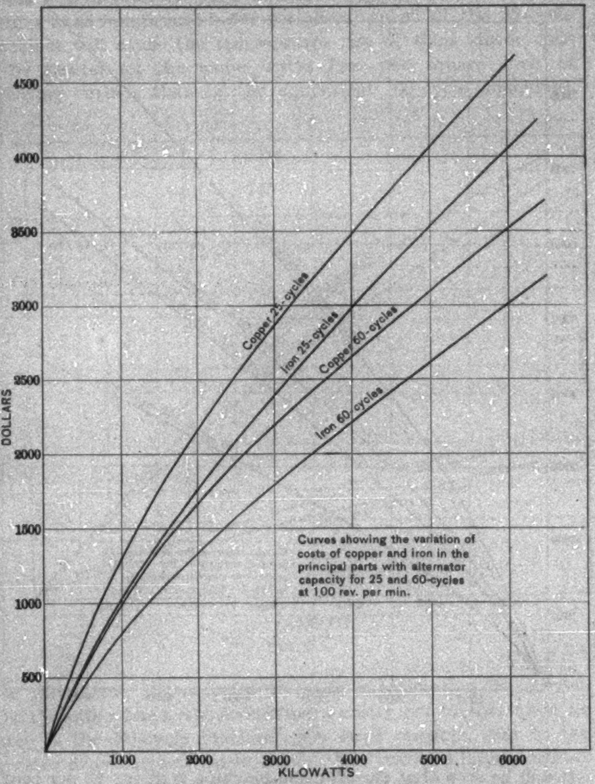
The costs of material previously considered, the material not included in the principal parts, the labor, rheostat, and exciter were added together, giving the actual factory cost of the entire equipment. In Fig. 10 these are plotted as " relative ", rather than " actual " costs, for the great difference in mechanical design of bases, bearings, etc., and the variation in labor, both as regards location and period, would influence the total cost of the equipment considerably; whereas the relative costs would not be greatly altered. This will be more evident when a com-



Curves showing the variation of weights of copper and iron in the principal parts with alternator capacity for 25 and 60-cycles at 300 rev.per min.

Fig. 6

parison of Figs. 8 and 10 is made; this comparison shows that the relative costs of the entire equipment and the material in the principal parts are nearly the same for the 25-cycle and 60-cycle machines operating at the same speed.



Curves showing the variation of costs of copper and iron in the principal parts with alternator capacity for 25 and 60-cycles at 100 rev. per min.

FIG. 7

Owing to the fact that bases, bearings, and shafts have been included in the total costs of machines operating at 300 rev. per min., and have been omitted for the 100 rev. per min.

machines, the 25-cycle equipment at 300 rev. per min. is more expensive than the 60-cycle at 100 rev. per min.; whereas the reverse is true when only the material in the principal parts is considered.

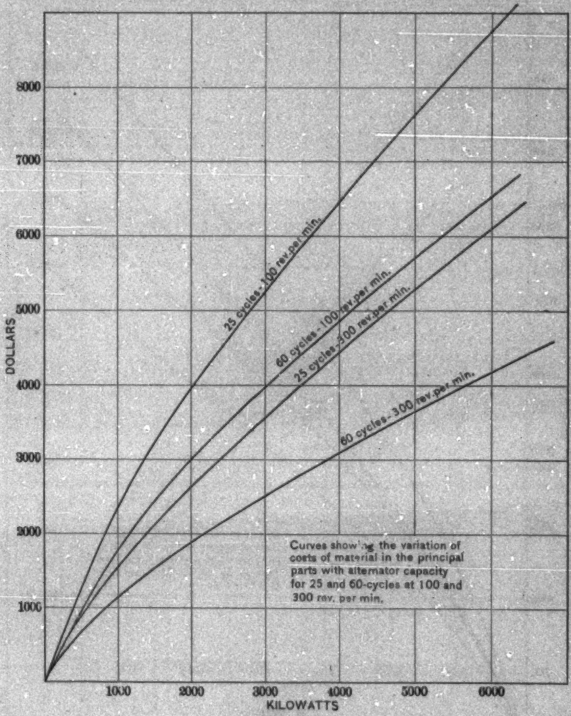


FIG. 8

It will be seen that the 25-cycle machine is about 42 per cent more expensive at 300 rev. per min., and 30 per cent more costly at 100 rev. per min., than the 60-cycle machine for the same output, voltage, and phase. This difference will be slightly greater in the high-speed machines for small outputs in which it is not possible with our present construction, when operating at low power-factors, to keep the temperature rise of the fields of the 25-cycle machines within reasonable limits, when that value of flux is employed to obtain the cheapest machine, unless a prohibitively large diameter be used. Moreover, the greater axial length and lower peripheral speed of the 25-cycle machines will cause the temperature rise of their stator coils to be greater for the same watts loss per square inch of radiating surface than in the equivalent 60-cycle machines,

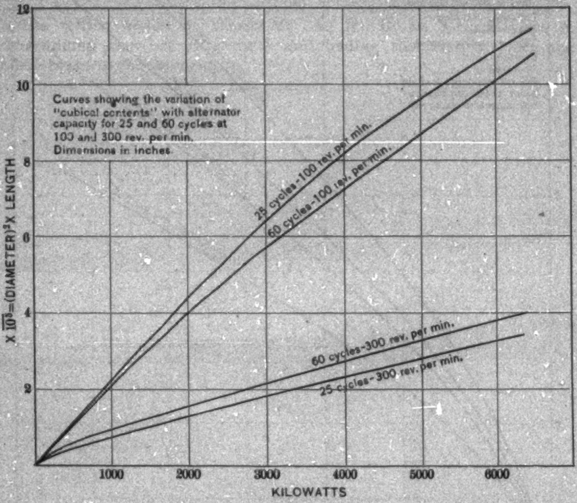


FIG. 9

for which due allowances were made in estimating the curves. On the other hand, somewhat more costly conductors must be used in the 60-cycle machines for large outputs, due to the greater eddy-current loss in them. The use of a larger number of stator slots causes the dies and windings to be somewhat more expensive in the slow-speed 60-cycle machine than in the 25-cycle machine for the same rating. This, combined with the fact that there are a greater number of poles in the slow-speed 60-cycle machines, will probably cause their cost to be somewhat more than was allowed for in estimating the curves in Fig. 10, thus causing the difference in cost between 25-cycle and 60-cycle machines at 100 rev. per min. to be slightly less than the curves indicate.

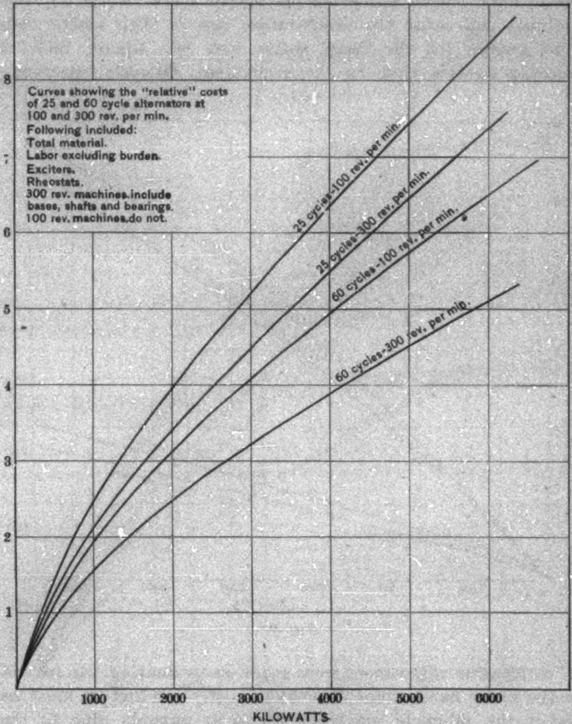


FIG. 10

The great weight of the poles and field copper of the 25-cycle alternators makes the cost of the rotors of 25-cycle machines guaranteed to stand a large overspeed, considerably greater than for the 60-cycle machines for the same rating. The great length of the end-connections of the stator coils for 25-cycle alternators for large outputs at high speeds makes it essential to support them. This is unnecessary in most 60-cycle alternators (excluding turbine-generators), inasmuch as the end-connections are shorter and the reactance of the stator is higher, both of which will tend to prevent the rupture of the end-connections due to the great rush of current at the first instant, when the alternator is short-circuited. We thus see that the difference between the costs of the 25-cycle and 60-cycle machines at 300 rev. per min. will probably be slightly more than would appear from an inspection of Fig. 10.

The writer wishes to thank Mr. A. N. Brown for assistance in determining the costs of exciters and finding the relation which the labor bears to the material.

DISCUSSION ON "COMPARATIVE COSTS OF 25-CYCLE AND 60-CYCLE ALTERNATORS." FRONTENAC, N. Y., JUNE 30, 1909

J. C. Lincoln: In Fig. 2, the curves showing the costs of 25-cycle machines, the cost of the armature copper, and the cost of the field copper lines cross each other at 2500 kw., showing the costs to be approximately equal. I have always thought that in a large machine the cost of the field copper would be several times that of the armature copper. Ordinarily the air-gap is very long in these machines, and that requires a large amount of copper in the revolving field in order to keep down the temperature, also good regulation requires considerable flux. These considerations tend to increase the ratio of the field copper to the armature copper.

Is it not true that in increasing the output of the armature from a 600 to 900 ampere conductor per inch the excitation has to be raised in almost the same proportion?

M. G. Lloyd: Fig. 10 seems to me somewhat unfair in that in comparing the total cost the 300-revolution machine should include base, shafts and bearings, while the 100-revolution machine does not. Not being engaged in the manufacturing end of the business, I do not know what proportion that cost bears to the total, but it might make quite a difference in the relative value of the costs.

Has Mr. Fechheimer made any comparisons of the cost with regard to the use of silicon steel in the same way? I know that it is not very much used as yet, but it seems probable that it is going to be used in alternators and in motors.

C. J. Fechheimer: With regard to Mr. Lincoln's question, pertaining to the crossing of the field and armature copper cost curves for 25 cycles at about 2400 kw. in Fig. 2; the relationship of these curves depends to a great extent upon the relative proportions of copper and iron. Until recently it was customary to use 500- or 600-ampere conductors per inch in a large generator, with the result that the field copper would be considerably more expensive than the armature copper. It was shown in my previous paper* that the product of excitation and weight of field copper varies approximately as the number of conductors, whereas the armature copper varies as the square of the number of conductors. Hence it will readily be seen that if the ampere conductors per inch be increased from 550 in a 500-kw. alternator to 900 in a 5000-kw. alternator, the armature copper will increase more rapidly than the field copper as the size of the alternator is increased. These are the values of ampere conductors per inch which correspond approximately to the most economical machines. Sometimes we cannot build the most economical machine, as, for example, as Mr. Lincoln states, the field heating becomes the limiting factor, and we must use a smaller value of ampere conductors per inch than corresponds to the most economical machine in order to keep the field temperature within reasonable limits. In general, however, we can in large machines with well ventilated, single-layer, edge-wound fields, prevent their temperature-rise exceeding 45 degrees cent. with full load at 85 per cent power-factor, which should be satisfactory.

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* TRANSACTIONS A. I. E. E. 1908, Vol. XXVII, p. 1429.

In regard to Dr. Lloyd's question as to including shafts, bearings, and bases, in Fig. 10; the 300-rev. per min. machines are intended to be water-wheel driven, in which cases the manufacturing companies are required to furnish these parts. Machines of 100 rev. per min. are usually engine-type machines, and with these the generator builder omits the shafts, bearings, and bases—the engine manufacturer supplies them.

As regards silicon steel, we have not made sufficient tests on the material for me to state definitely whether it would pay us to use it or not. I therefore omitted it in this comparison. We hope to make more complete tests in the future.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

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CALCULATION OF IRON LOSSES IN DYNAMO ELECTRIC MACHINERY

BY I. E. HANSSEN

It is well known that the iron losses in all kinds of electric motors and generators are invariably much greater than those calculated from iron-loss curves, such as are obtained from tests of samples of iron, unless an allowance is made for additional losses.

The causes of this increase in the losses are many and varied. They have been dealt with in detail by various writers, but so far as the writer knows, a simple method for predetermining the total iron loss has never appeared in print. The losses in the different parts of the magnetic circuit will be considered in a general way and the causes of the additional losses will be pointed out. It is hoped that this paper will be of some use to designers in pointing out a method which has been found successful in actual practice after about one and a half years use.

Consider a smooth-core armature of a generator for either direct or alternating current. The paths of the flux are shown in Figs. 1, 2, and 3. It will be noticed that the distribution lacks uniformity more or less, due to the difference in the length of the paths. This lack of uniformity naturally leads to an increase of the losses above what they would be were the distribution uniform.

An allowance must further be made to take care of imperfect insulation between the discs, caused by filing, burrs, and crushing of the insulating material when subjected to pressure, and also for the hardening effect caused by the punching process if the discs are not again annealed.

To prevent the teeth from bulging out, a number of extra heavy discs are usually placed at the ends of the core and next to the ventilating ducts if such are provided. These heavy discs, being from two to three times thicker than the regular ones, will have from four to nine times greater eddy current losses. Sometimes these discs have a higher permeability than the thinner ones, and this will still further increase the losses due to the higher induction which will exist in the thicker discs.

Iron-loss curves of iron samples, as usually made, give the losses taking place when the iron is subjected to an alternating magnetic field. The field in an armature, however, is not an alternating one but is of a rotary nature, probably elliptical. Such a field is generally conceded to cause considerably higher iron losses than the alternating field, provided the density at which the iron is worked does not exceed a certain limit. This limit is reached at about 120,000 c. g. s. lines per square inch. If the density is increased above this value, the loss per unit of iron decreases rapidly. However, such high densities are hardly ever reached in armature cores, except in the teeth, so that there is generally a further allowance to be made, due to the field being a rotating one.

In a smooth-core armature, the foregoing probably covers all the additional iron losses in the machines, provided the armature and field structure are perfectly concentric. If they are not concentric, the gap reluctances will vary with different positions of the armature, the result being that the flux in the field poles and yoke will not have a constant value but will pulsate and thus produce eddy currents in the field structure. *Dr. W. M. Thornton, who first called attention to this fact, cites a case in which this loss amounted to 2300 watts for a 10-kw. generator.

Assuming that the armature and field structure are concentric, the actual iron loss, due to the above-mentioned causes, will be from 25 per cent to 35 per cent greater than calculated from the iron curves for smooth-core armatures.

Toothed armatures. What has just been said about smooth-core armatures applies equally well to the iron back of the slots of toothed armatures, the only difference being that in the latter

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*See Journal of the Institution of Electrical Engineers V-33, page 545.

Figures 1, 2, 3, 4, 5, and 6 are reproduced from the paper by Prof. W. M. Thornton, referred to previously. Figures 7, 8, and 9 are taken from a paper by Hele-Shaw, Hay & Powell, Journal of the Institution of Electrical Engineers, Vol. 37, No. 179.

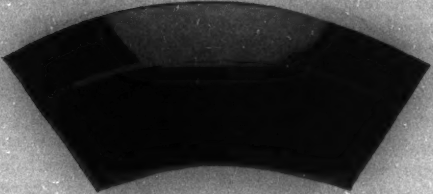

FIG. 1

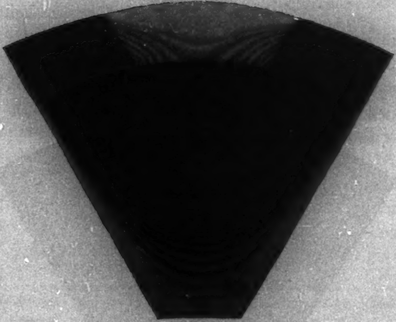

FIG. 2

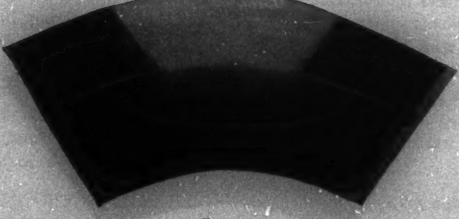

FIG. 3

Stream lines of magnetic induction in smooth cores

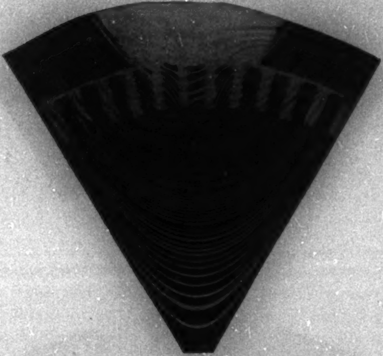

FIG. 4

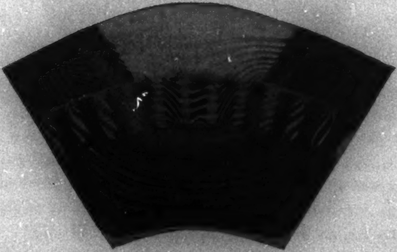

FIG. 5

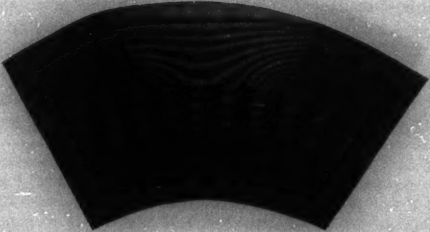

FIG. 6

Lines of magnetic induction in toothed cores the distribution is less uniform, as an inspection of Figs, 4, 5, and 6 will show. It will be seen that for some distance back of the teeth the density is higher than back of the slots, and of the same order as the density in the teeth. If the iron is nearly saturated, these streamers of higher density appear to continue all the way from pole to pole, as pointed out by Dr. Thornton. It is probable that this phenomenon nullifies somewhat the reduction of the iron loss which would otherwise occur when iron subjected to a rotating field is worked above 120,000 lines per square inch.

The writer has found that adding 30 per cent, 35 per cent, and 40 per cent for 25, 40, and 60 cycles, respectively, to the calculated loss in the iron back of the slots, gives very nearly correct results.

Losses in the teeth. In the teeth the percentage increase in the losses due to filing and burrs may become much greater than is the case for the part of the iron already discussed, particularly in high-frequency machines (50 and 60 cycles), in which the eddy currents in the burrs become very marked. Here also we have to allow for the thicker discs next to the ventilating ducts and at the core ends. Furthermore, due to the leakage field, the resultant field is elliptical instead of alternating. An addition of 30 per cent, 60 per cent, and 80 per cent, for 25 40, and 60 cycles, respectively, has been found to give satisfactory results.

Losses due to slot openings. In addition to the losses already mentioned there are other losses, particularly in machines having wide-open slots, caused by variations in the gap density. In direct-current and synchronous machines these losses are produced by eddy currents in the pole-shoes, while in induction motors they are caused partly by eddy currents in the tooth-faces and partly by density variations extending throughout the depth of the teeth. Fig. 10 shows roughly the flux distribution in a portion of the gap of a direct-current machine or in a synchronous machine with projecting poles. As will be seen, the density opposite a slot is lower than that opposite a tooth, the result being that the pole-shoe is subjected to the influence of a high-frequency field.

The frequency of this field is $\frac{\text{rev. per min.} \times S}{60}$ cycles per second, S being the number of armature slots.

In an induction motor in which both the primary and second-

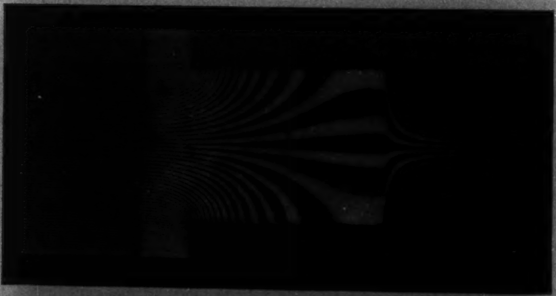

FIG. 9

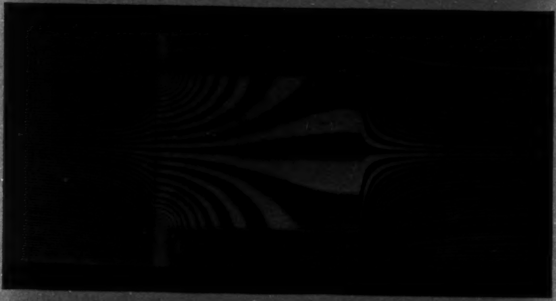

FIG. 8

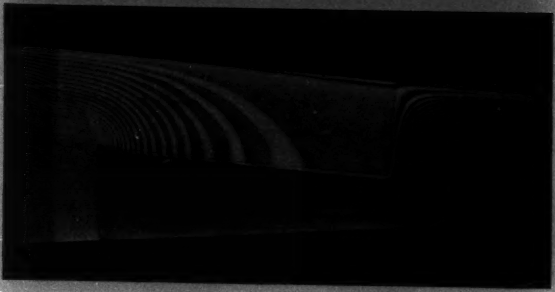

FIG 7

ary members are slotted, both members will be subjected to these pulsations. However, as the secondary slot openings are generally very small, the losses from this source in the primary iron will as a rule be of no great moment.

The frequency of the pulsations in the secondary member is $\frac{\text{rev. per min.} \times S\,p}{60}$ cycles per second, where $S\,p$ is the number of primary slots, while to obtain the frequency in the primary the number of secondary teeth is substituted for the number of primary teeth in this expression. The amount of variation in density can be calculated quite accurately, but this requires a considerable amount of time, and experience indicates that this refinement is not justified.

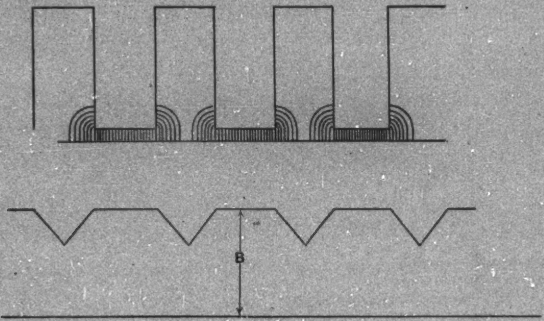

FIG. 10

Within practical limits of slot and gap dimensions, the variation can be said to be roughly proportional to the expression: k/δ

where δ = air-gap.
k = slot opening.

As the losses are caused mainly by eddy currents, while the hysteresis loss is much smaller, the lotal losses from this source will vary nearly as the square of the frequency and probably approximately as $\left(\frac{k}{\delta}\right)^2$. Therefore it should be possible to plot curves of the expression $\frac{B\,k\,s\ \text{rev. per min.}}{\delta}$ against watts loss per square inch of iron surface in the air-gap, B being the maximum density in kilolines per square inch of secondary tooth face, fringing being neglected.

In the case of alternating-current machines, in which only a few standard frequencies come into consideration, it is probably more accurate to plot the curves using the expression $\frac{B\,k\,s}{\delta\,p}$ making a curve for each frequency to be used. The necessary data can be obtained by determining the losses in the teeth and in the portion of the core back of the teeth in the manner already explained, deducting the value thus obtained from the iron loss observed on test.

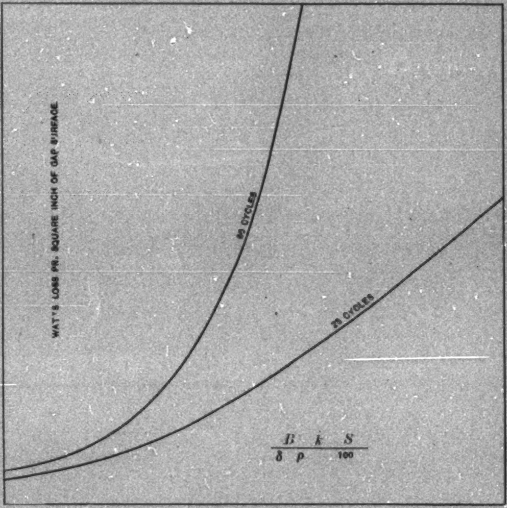

FIG. 11

In direct-current machines and in alternating-current machines having projecting poles, the result will represent the loss in the pole shoes, provided the rotating and stationary parts are concentric.

In machines with distributed field windings and in induction motors, part of the result represents losses in the primary and part in the secondary. It is possible in such a case to separate the two, but it is easier to obtain the necessary data from machines with projecting poles, and in the case of induction motors by choosing machines in which the secondary slot openings are small and the number of secondary slots less than that of the primary.

Curves obtained in this manner have been used by the writer and others with satisfactory results. The general form of such curves is shown by Fig. 11. In obtaining the data for these curves, it is necessary to distinguish between laminated surfaces which are not finished and such as are either ground or turned. A slight cut in the lathe will increase the surface losses about 50 per cent, while grinding may affect them more or less than this, the increase being greater for coarse wheels applied under considerable pressure.

In induction motors in which the air-gap necessarily is very short, wide-open slots are often objectionable, particularly in high-speed machines, as the iron loss due to the slot openings will often equal the losses due to the variations of the main field. This can be easily understood when it is known that for a 60-cycle machine, in which for the primary $\frac{B\,k\,s}{\delta\,P\;100} = 150$, this loss amounts to about 7 watts per square inch of secondary iron surface exposed to the gap.

Moreover, in comparing the running iron loss of an induction motor with the iron loss at standstill, it will in many cases be found that the former exceeds the iron loss at standstill although in the latter case the secondary iron is subjected to the full frequency of the line.

DISCUSSION ON "CALCULATION OF IRON LOSSES IN DYNAMO ELECTRIC MACHINERY." FRONTENAC, N. Y., JUNE 30, 1909.

R. E. Hellmund: Mr. Hanssen says that the teeth of dynamo electric machines are subject to a rotary magnetization by reason of leakage. Though some of the leakage fluxes actually pass the teeth crosswise, the leakages are so small compared with the main flux that the statement does not seem quite justified. This, of course, is not of great importance. In designing induction motors I have found Mr. Hanssen's method to be most useful. Other methods given for calculating surface losses are either too complicated to be of practical use or the results obtained by them are too inexact. Mr. Hanssen's method represents a very good compromise between exact theory and purely empirical formulas. It is, of course, not to be expected that any method for calculating core losses will always give correct results, it being well known that machines of the same type manufactured at the same time show core losses differing from each other as much as 20 per cent, sometimes even more. I have found, however, that the results obtained by Mr. Hanssen's method have always come close to the average value of the tests on a number of machines of the same type.

A. E. Averett: There are certain features of this paper which seems to me to be more of a specific than a general feature. In one part of the paper certain corrections should I think be applied to a specific type of machine. As soon as the type is changed, or the proportion of the iron in the teeth and in the yokes, the corrections will have to be changed.

Near the end of the paper it is said that a slight cut in the lathe will increase the core-loss about 50 per cent. I think that point is open to question. I have seen machines in which the rotors have been turned and in which the core-losses have not been increased appreciably; that is, with any commercial test the difference could not be detected. Again, I have seen machines where the core-loss has been nearly doubled. I think if the rotor is properly turned it will very seldom increase the core-loss appreciably.

In the high-frequency machines, silicon steel decreases the core-loss very much; for this reason I think it advisable to use it in spite of its increased cost.

V. Karapetoff: In estimating iron losses in revolving machinery it is not safe to rely upon the results obtained with stationary samples, because the distribution of the flux is far too irregular in space as well as in time. The safest procedure is to determine the actual iron loss from tests on a large number of actually built machines, at various densities and frequencies, and then use these data. In doing so, it will be found that the expression: total iron loss $= a\,B + b\,B^2 + c\,B^3$ comes much closer to the experimental curves than the formula $\eta\,B^n$. Here B is flux density, and a, b, c, are empirical coefficients.

In regard to Figs. 1 to 9 given in Mr. Hanssen's paper: These are not photographs of actual lines of force, but of some fluid flowing between two plates of glass. Into this fluid some coloring matter is injected, and then the apparatus is projected by means of a lantern or photographed. To my knowledge, the method was first used by Professor Hele-Shaw. The only difference between the assumed distribution of magnetism and the flow of the water between two parallel plates of glass is that water has inertia while the magnetic lines are devoid of inertia. By making the water flow very slowly the effect of inertia is practically eliminated, and in order to make the analogy complete paths are provided whose mechanical resistances to flow are in the same ratio as the magnetic reluctances of the air-gap and the iron teeth.

The streaks seen in Figs. 1 to 9 represent the actual directions of the streams of water. The light streaks between the poles are not assumed or anticipated, but show that, while the reluctance there is high, nevertheless some water prefers to flow into the narrow space between the poles, instead of going around through the armature. This illustrates magnetic leakage between the poles.

I. E. Hanssen (by letter): It is true, as stated by Mr. Hellmund, that the leakage flux is small compared with the main flux; for this reason the paper states that the teeth are subjected to an elliptical field, not to a rotary field as Mr. Hellmund says. However, as the path of the leakage flux is limited to a relatively small section the resulting density may become quite high, and consequently should be considered.

Mr. Averett states that as soon as the type of machine or the proportions of the iron in the teeth and yoke are changed the corrections will have to be changed. Such is the case when the older methods are used; however it is not so with the proposed method, as here the principal losses are estimated individually and it is equally good for all proportions of iron in teeth and iron in yoke. Mr. Averett has evidently misread the statement referring to the increase in the losses due to machining the air-gap surface. The paper says that a slight cut in the lathe increases the surface losses, (the losses due to the slot openings) some 50 per cent while Mr. Averett seems to think that reference is made to the total iron loss.

In a machine having narrow slot openings and relatively large air-gap the losses due to the slot openings are small; consequently, increasing them 50 per cent may not appreciably affect the total iron loss; if, on the other hand, the slot openings are large compared with the air-gap, then the increase in the total losses will be quite important, in most cases.

When comparing the losses before and after turning the rotor, it must be remembered that the turning process increases the length of the air-gap, which tends to reduce the surface losses; this must of course be taken into account, otherwise the results will be altogether misleading. If a heavy cut were made on the rotor of a machine, with say an air-gap of 0.020 in., we would probably find that the core loss would be decreased.

The writer cannot agree with Professor Karapetoff in what he says about the manner of estimating iron losses. The method outlined by the writer has been applied to several hundred machines with widely differing characteristics, and it has always given excellent results. Estimating core losses by comparison is, on the other hand, a very uncertain proposition particularly when, as is often the case, it becomes necessary to use very large slot openings or proportions out of the ordinary.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 30, 1909.

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ELECTRICAL MEASUREMENTS ON CIRCUITS REQUIRING CURRENT AND POTENTIAL TRANSFORMERS

BY L. T. ROBINSON

Modern requirements make it necessary to measure alternating current, volts, and watts on circuits where the magnitude of these quantities and the safety of the operator require that some means be provided so that the instruments used are not directly connected to the circuit. In certain special measurements it may be found accurate and convenient to use resistances to multiply the indications of the instrument, these resistances being used as shunts to the current coil or in the potential coils of voltmeters or wattmeters.

In a great majority of cases the most convenient arrangement is that of employing current and potential transformers. It is, therefore, necessary to be able to determine with exactness the ratio of these transformers under various conditions of frequency, voltage etc., to which they may be subjected in use. In connection with the measurement of watts it is also necessary to consider the phase displacement between the primary and the secondary current or voltage used on the transformers.

It is the purpose of the present paper to discuss, briefly, from a practical point of view, the causes which make certain corrections necessary either in the manufacture of the transformer or in their use; the most suitable methods for determining the variations in transformer ratio and phase-angle; the general order of magnitude of these errors or corrections and the most convenient way in which the known values can be made use of to correct the instrument readings which have been obtained. Before considering the question of transformers it may be well to discuss briefly certain points which relate to the instruments alone. In measuring amperes on alternating-current circuits, if ammeters are provided, having no correction factor due to frequency or wave-form, and which, therefore, measure directly the effective value of the current flowing, they may be tested on direct current. If without hysteresis as well, they may be used on alternating-current circuits without error.

Most ammeters which have been found useful for commercial purposes are not entirely free from one or more of these errors, and to obtain the most accurate results which they are capable of giving, they must be tested on an alternating-current circuit of the same order of frequency as that on which they are to be used. In some instruments the range of frequency, wave-form etc. over which they may safely be employed, is greater than that found in any usual application, while others may be applicable to accurate measurements only within much closer limitations. However, it may be said that ammeters are readily obtainable both for switchboard and for portable use, the errors, due to any conditions under which the ammeters may be used, being so small that they may be neglected. If these meters are once calibrated on an alternating-current circuit of, say, 60 cycles, they may be used on any commercial frequency or wave-form without sensible error.

It is in general true that ammeters can be made having only a limited current-carrying capacity; and for measurements of current beyond this range, as well as for use on circuits where protection against high voltage is required, some arrangements are neccesary for causing a known part of the current to pass through the ammeter. The most satisfactory arrangement is the current transformer. For use with ammeters it is necessary to know the relation between the primary and the secondary currents under various conditions in which ammeters and other devices, having a different total resistance and reactance, are included in the secondary of the transformer.

In measuring volts somewhat similar considerations apply, with slight modifications, although in this case potential transformers of known ratio must be used.

In measuring watts, either current or potential transformers or both may be required. In addition to errors similar to those found in ammeters and voltmeters, but usually much less, in fact usually too small to be considered at all, wattmeters have an inherent error appearing as an effect equivalent to a displacement between the current in the moving coil—potential circuit—

and the electromotive force impressed upon the circuit to be tested.

It has been customary in theoretical discussions to compute this angle from the resistance and inductance of the potential circuit, but there are various other actions within a wattmeter that make it necessary to determine, by suitable means, this equivalent angle as it exists in the instrument. The discussion of the magnitude of this quantity, and of the most suitable means for determining it, is not the purpose of the present paper. It will be assumed that such an equivalent angle has either been determined or is too small appreciably to affect the results under the conditions in which the instrument is to be used. This angle is different for different frequencies and is also affected in somewhat imperfect instruments, due to other causes. Therefore, in speaking of this angle it must not be considered that it can be assigned a fixed value in all cases, but that a value for the angle is chosen which is suitable for the immediate conditions under which the instrument is used.

In using current or potential transformers with a wattmeter it is well known that the phase-angle between the primary and the secondary of the transformer must be taken into account, if the most accurate results are to be obtained. It may also be said that usually the effect of these transformer angles, especially when current transformers are used, is to cause errors in the indications of the wattmeters much geater than those caused by the equivalent angle of the instrument alone. Before proceeding to the consideration of ratio and phase-angle in current and potential transformers it is well to discuss the relation that these various angles have to the results obtained when wattmeters are used. The ratios of any transformers used have, of course, the same effect on a wattmeter as on an ammeter and voltmeter.

Before discussing the means which may be employed to determine the ratio and phase-angle in current and potential transformers it may be well to state briefly the effect which these angles will have on the indications of a wattmeter with which they are used. We will call the equivalent angle of phase displacement in the wattmeter α, the angle of phase displacement in the current transformer β, and the same quantity in the potential transformer γ. In an instrument in which the eddy currents have been quite completely eliminated, the angle represents a lag in the potential circuit, and when so existing will be given the positive sign, or $+\alpha$. In some instruments, however, due to causes which have been briefly referred to, this correction appears as an effect equivalent to leading current in the potential circuit, in which case the equivalent correction angle will be written as $-\alpha$.

Current transformers, as usually made, when carrying an instrument load give leading current in the secondary circuit. The effect of this is the same on the connected wattmeter as lagging current in its potential circuit, and, therefore, leading current in the secondary of the current transformer will be written $+\beta$.

Potential transformers, as usually made, give leading potential in the secondary, which affects the instrument in the same way as some cause within the instrument, which would make the current lead in the potential circuit; therefore, leading potential in the potential transformer will be written $-\gamma$.

It is useful to remember that in all cases correction angles tending to decrease the phase displacement between the current and the potential circuits in the instrument are to be considered as positive, and those tending to increase the phase displacement as negative; so that if the sum of the correction angles is positive, the wattmeter reading will, with lagging current, be greater than the true watts.

We will consider lagging current in the main circuit to be represented by a positive angle θ, and leading current by the same symbol with a negative sign $-\theta$. The reading on any wattmeter, divided by the volt-amperes, is equal to the apparent power-factor. Using $\cos \theta_2$ to represent the apparent power-factor of the circuit we can write

$$\text{Cos}\, \theta_2 = \frac{\text{wattmeter reading}}{\text{volt-amperes}} = \text{apparent power-factor} =$$

$$\cos\, (\theta \pm \alpha \pm \beta \pm \gamma) \text{ or } \cos \theta = \cos\, (\theta_2 \mp \alpha \mp \beta \mp \gamma)$$

where α, β, γ are the correction angles above referred to, which have been added with their proper sign to the angle of lag θ_2. If the angle θ_2 is leading it may be considered as a negative angle so that negative correction angles added to it will increase the total angle, or vice versa.

The ratio of the true power-factor to the apparent power-factor is naturally the correction to be applied to the indications of the instrument, as the instrument reading is due to the apparent power-factor. Therefore, the following relation holds.

$$\text{wattmeter reading} \times \frac{\cos\theta}{\cos\theta_2}$$

$$= \text{wattmeter reading} \times \frac{\text{true power-factor}}{\text{apparent power-factor}} = \text{true watts}$$

In some instances, when using wattmeters of small capacity it is necessary to correct the instrument reading for the losses in the instruments used. Usually the correct way to do this is to connect the voltmeter and the potential winding of the wattmeter in such a way that the energy consumed in them is measured by the wattmeter, as a part of the total watts. Sometimes this correction amounts to a considerable part of the total reading of the wattmeter. The instrument reading is then made up of two parts, one of which, the loss in the potential circuits of the instruments, is nearly or quite non-inductive, while the other may be inductive, and therefore require correction. It is still correct to use the total watts determined in this way in obtaining the apparent power-factor, and after the correction has been applied the measured or computed losses in the potential circuits may be deducted.

Perhaps the process can be best illustrated by examples. In the first case the correction is applied to an instrument used alone whose equivalent phase-angle is known, and in the second case current and potential transformers are used. In the first case also the watts lost in the potential circuit of the instrument itself have been subtracted, and in the second case this quantity is too small to be considered.

Example 1,

lagging load, 60 cycles, $P3$ wattmeter, volts 100, amperes 10.
resistance of wattmeter potential circuit 2500 ohms.
resistance of voltmeter potential circuit 2200 ohms.

$$\text{Watts consumed in instruments } \frac{100^2}{2500} + \frac{100^2}{2200} = 8.5 \text{ watts.}$$

Watts read corrected for scale error $= W = 100$
$\alpha = +3$ minutes

$$\frac{W}{V\ A} = \cos\theta_2 = \frac{100}{1000} = 0.1$$

Therefore, θ_2 = 84 degrees 16 min. (cos = 0.0999) and
$\theta = \theta_2 + \alpha$ = 84 degrees 19 min. (cos = 0.099).

True watts $= \dfrac{100 \times 0.099}{0.0999} = 99$. From this we subtract 8.5, the instrument losses, leaving 90.5, the required value.

Using the same values as above with leading load,

$\dfrac{W}{V\ A} = \cos\theta_2 = \dfrac{100}{1000} = 0.1$, therefore, $\theta_2 = -84$ degrees 16 min. (cos 0.0999)
and $\theta = -\theta_2 + \alpha = -(\theta_2 - \alpha) = -84$ degrees 13 min. (cos = 0.1008

true watts $= \dfrac{100 \times 0.1008}{0.0999} = 101$ nearly.

Subtracting instrument losses, 8.5 watts, we have 92.5 watts, the required value.

Example 2,

lagging load, 25 cycles,
current transformer, ratio 39.64:1, (99.1×40 from curve)
potential transformer, ratio 19.94:1,
volts 104.4×19.94 = 2082.
amperes 2.5×39.64 = 99.1
V A 206,360. Wattmeter reading 53.
apparent watts = 53×39.64×19.94.=0.41893.

$$\operatorname{Cos}\theta_2 = \frac{41{,}893}{206{,}360} = 0.20301,$$

therefore θ_2 = 78 degrees 17 min. 20 sec.

α at 25 cycles is negligible.

$\beta = +55$ min.; $\gamma = -38$ min.; θ = 78 degrees 17 min. 20 sec. +55 min. − 38 min. or 78 degrees 34 min. 20 sec.

Cos θ = 0.1981. Then the true watts $= 41893 \times \dfrac{0.1981}{0.203} = 40880$.

As in the first example, the instrument and potential transformer losses are to be subtracted, if appreciable and if the connection used requires it. In this example they are too small to be considered. If the load is leading, the sign of θ_2 is to be changed as in example 1.

To be useful in practical work some arrangement must be provided, whereby the necessary computations may be quickly made, and for this purpose Table I and Table II have been

TABLE I

$\frac{\cos\theta}{\cos\theta_2}$ LAGGING LOAD WITH $(\alpha+\beta+\gamma)$ POSITIVE
LEADING LOAD WITH $(\alpha+\beta+\gamma)$ NEGATIVE

Power factor $\cos\theta_2$

$\alpha+\beta+\gamma$	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90
5′	0.9855	0.9904	0.9928	0.9943	0.9953	0.9966	0.9974	0.9980	0.9985	0.9989	0.9993
10′	0.9710	0.9808	0.9857	0.9887	0.9907	0.9933	0.9949	0.9961	0.9970	0.9978	0.9985
15′	0.9565	0.9712	0.9786	0.9831	0.9860	0.9399	0.9924	0.9941	0.9955	0.9967	0.9978
20′	0.9420	0.9616	0.9714	0.9774	0.9814	0.9866	0.9898	0.9922	0.9940	0.9956	0.9971
25′	0.9276	0.9520	0.9643	0.9718	0.9768	0.9832	0.9873	0.9902	0.9925	0.9945	0.9964
30′	0.9131	0.9424	0.9571	0.9661	0.9722	0.9799	0.9848	0.9883	0.9910	0.9934	0.9956
40′	0.8841	0.9232	0.9429	0.9548	0.9629	0.9732	0.9797	0.9844	0.9880	0.9912	0.9942
50′	0.8552	0.9040	0.9286	0.9436	0.9537	0.9665	0.9747	0.9805	0.9850	0.9890	0.9928
1°	0.8262	0.8848	0.9143	0.9323	0.9444	0.9598	0.9696	0.9766	0.9820	0.9868	0.9914
10′	0.7971	0.8655	0.8999	0.9210	0.9350	0.9530	0.9645	0.9726	0.9789	0.9845	0.9899
20′	0.7681	0.8463	0.8857	0.9097	0.9257	0.9463	0.9594	0.9687	0.9759	0.9822	0.9884
30′	0.7391	0.8271	0.8713	0.8984	0.9164	0.9396	0.9543	0.9647	0.9729	0.9800	0.9869
40′	0.7101	0.8079	0.8570	0.8872	0.9071	0.9329	0.9491	0.9608	0.9699	0.9777	0.9854
50′	0.6811	0.7887	0.8427	0.8759	0.8978	0.9261	0.9440	0.9568	0.9668	0.9755	0.9839
2°	0.6521	0.7695	0.8284	0.8646	0.8885	0.9194	0.9389	0.9529	0.9638	0.9732	0.9824
10′	0.6230	0.7502	0.8140	0.8531	0.8791	0.9126	0.9337	0.9488	0.9607	0.9709	0.9808
20′	0.5940	0.7309	0.7996	0.8417	0.8697	0.9058	0.9286	0.9448	0.9576	0.9686	0.9793
30′	0.5649	0.7116	0.7853	0.8303	0.8604	0.8990	0.9234	0.9408	0.9545	0.9663	0.9778
40′	0.5359	0.6924	0.7709	0.8189	0.8510	0.8922	0.9183	0.9368	0.9514	0.9640	0.9763
50′	0.5068	0.6731	0.7566	0.8074	0.8417	0.8855	0.9131	0.9328	0.9483	0.9617	0.9748
3°	0.4778	0.6538	0.7422	0.7960	0.8323	0.8787	0.9080	0.9288	0.9452	0.9594	0.9733
10′	0.4487	0.6343	0.7277	0.7845	0.8228	0.8718	0.9028	0.9247	0.9420	0.9570	0.9717
20′	0.4196	0.6148	0.7133	0.7731	0.8134	0.8650	0.8976	0.9207	0.9389	0.9547	0.9701
30′	0.3906	0.5953	0.6989	0.7617	0.8040	0.8582	0.8924	0.9166	0.9358	0.9523	0.9685
40′	0.3615	0.5759	0.6845	0.7503	0.7946	0.8514	0.8871	0.9126	0.9327	0.9500	0.9670
50′	0.3325	0.5564	0.6701	0.7388	0.7852	0.8445	0.8819	0.9085	0.9295	0.9476	0.9654
4°	0.3034	0.5369	0.6557	0.7274	0.7758	0.8377	0.8767	0.9045	0.9264	0.9453	0.9638
10′	0.2743	0.5177	0.6412	0.7159	0.7663	0.8308	0.8714	0.9004	0.9232	0.9428	0.9621
20′	0.2452	0.4985	0.6268	0.7045	0.7569	0.8239	0.8662	0.8963	0.9200	0.9404	0.9605
30′	0.2161	0.4793	0.6124	0.6930	0.7474	0.8171	0.8609	0.8922	0.9168	0.9380	0.9590
40′	0.1871	0.4602	0.5980	0.6816	0.7380	0.8102	0.8557	0.8881	0.9136	0.9356	0.9573
50′	0.1580	0.4410	0.5836	0.6701	0.7285	0.8034	0.8504	0.8841	0.9104	0.9332	0.9557
5°	0.1289	0.4218	0.5692	0.6587	0.7191	0.7965	0.8452	0.8800	0.9072	0.9308	0.9540
10′	0.0998	0.4026	0.5548	0.6472	0.7096	0.7896	0.8399	0.8759	0.9040	0.9284	0.9524
20′	0.0707	0.3834	0.5404	0.6358	0.7002	0.7828	0.8347	0.8718	0.1008	0.9260	0.9507

TABLE II

$\frac{\cos\theta}{\cos\theta_2}$ LAGGING LOAD WITH $(\alpha+\beta+\gamma)$ NEGATIVE
LEADING LOAD WITH $(\alpha+\beta+\gamma)$ POSITIVE

Power factor $\cos\theta_2$

$\alpha+\beta+\gamma$	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90
5′	1.0145	1.0096	1.0071	1.0057	1.0046	1.0033	1.0025	1.0020	1.0015	1.0011	1.0070
10′	1.0289	1.0192	1.0142	1.0113	1.0092	1.0066	1.0050	1.0039	1.0029	1.0022	1.0014
15′	1.0434	1.0288	1.0213	1.0170	1.0138	1.0099	1.0075	1.0059	1.0044	1.0033	1.0021
20′	1.0578	1.0383	1.0284	1.0225	1.0185	1.0133	1.0100	1.0077	1.0059	1.0043	1.0028
25′	1.0723	1.0479	1.0355	1.0282	1.0231	1.0166	1.0125	1.0097	1.0074	1.0054	1.0035
30′	1.0867	1.0575	1.0426	1.0338	1.0277	1.0199	1.0150	1.0116	1.0088	1.0065	1.0041
40′	1.1156	1.0766	1.0568	1.0450	1.0369	1.0265	1.0200	1.0154	1.0117	1.0086	1.0055
50′	1.1445	1.0958	1.0711	1.0563	1.0462	1.0332	1.0250	1.0193	1.0147	1.0108	1.0069
1°	1.1734	1.1150	1.0853	1.0675	1.0554	1.0398	1.0300	1.0231	1.0176	1.0129	1.0083
10′	1.2023	1.1342	1.0995	1.0787	1.0646	1.0464	1.0350	1.0269	1.0205	1.0150	1.0096
20′	1.2311	1.1533	1.1136	1.0899	1.0737	1.0530	1.0399	1.0307	1.0234	1.0171	0.0110
30′	1.2600	1.1725	1.1278	1.1010	1.0829	1.0595	1.0449	1.0345	1.0262	1.0192	1.0123
40′	1.2888	1.1916	1.1419	1.1122	1.0920	1.0661	1.0498	1.0383	1.0291	1.0213	1.0136
50′	1.3177	1.2108	1.1561	1.1234	1.1012	1.0727	1.0548	1.0421	1.0320	1.0235	1.0150
2°	1.3466	1.2300	1.1703	1.1346	1.1104	1.0793	1.0598	1.0459	1.0349	1.0256	1.0163
10′	1.3754	1.2492	1.1844	1.1462	1.1195	1.0858	1.0647	1.0497	1.0377	1.0277	1.0176
20′	1.4042	1.2683	1.1985	1.1578	1.1286	1.0924	1.0696	1.0534	1.0406	1.0297	1.0189
30′	1.4329	1.2875	1.2126	1.1693	1.1377	1.0989	1.0745	1.0572	1.0435	1.0318	1.0201
40′	1.4617	1.3066	1.2267	1.1809	1.1468	1.1054	1.0794	1.0609	1.0463	1.0338	1.0214
50′	1.4905	1.3258	1.2409	1.1925	1.1560	1.1120	1.0844	1.0647	1.0492	1.0359	1.0227
3°	1.5193	1.3449	1.2550	1.2041	1.1651	1.1185	1.0893	1.0684	1.0520	1.0379	1.0240
10′	1.5480	1.3637	1.2690	1.2147	1.1742	1.1250	1.0942	1.0721	1.0548	1.0399	1.0252
20′	1.5769	1.3824	1.2831	1.2253	1.1832	1.1315	1.0990	1.0758	1.0576	1.0419	1.0264
30′	1.6056	1.4012	1.2971	1.2359	1.1923	1.1379	1.1039	1.0795	1.0603	1.0438	1.0276
40′	1.6344	1.4199	1.3111	1.2465	1.2013	1.1444	1.1087	1.0832	1.0631	1.0458	1.0288
50′	1.6632	1.4387	1.3252	1.2572	1.2104	1.1509	1.1135	1.0869	1.0660	1.0478	1.0300
4°	1.6920	1.4575	1.3392	1.2678	1.2194	1.1574	1.1184	1.1096	1.0687	1.0498	1.0313
10′	1.7206	1.4764	1.3532	1.2788	1.2284	1.1638	1.1232	1.0942	1.0714	1.0518	1.0325
20′	1.7491	1.4952	1.3672	1.2898	1.2374	1.1703	1.1280	1.0979	1.0742	1.0537	1.0337
30′	1.7777	1.5141	1.3811	1.3007	1.2463	1.1767	1.1328	1.1015	1.0769	1.0557	1.0348
40′	1.8062	1.5329	1.3951	0.3117	1.2553	1.1831	1.1376	1.1051	1.0796	1.0576	1.0360
50′	1.8348	0.5518	1.4091	1.3227	1.2643	1.1896	1.1424	1.1088	1.0824	1,0596	1.0372
5°	1.8634	1.5707	1.4231	1.3337	1.2733	1.1960	1.1472	1.1124	1.0851	1.0616	1.0384
10′	1.8920	1.5896	1.4371	1.3447	1.2823	1.2024	1.1520	1.1160	1.0878	1.0636	1.0306
20′	1.9205	1.6084	1.4511	1.3557	1.2913	1.2089	1.1568	1.1196	1.0906	1.0655	1.0408

prepared. With the aid of these tables, knowing $\cos\theta_2$ or the apparent power-factor and the angles α, β, γ, the correction factor $\frac{\cos\theta}{\cos\theta_2}$ can be obtained at once.

Table I gives the multipliers for use when $\alpha \pm \beta \pm \gamma$ has various values from 5 min. to 5 degrees 20 min., and when the power-factor varies between the 0.1 and 0.9. Any power-factor above 0.9 may be corrected for by interpolating between the 0.9 value and unity for the required angle. The correction at unity power-factor for small angles is too small to be usually considered.

Table I is to be used when the load under test is lagging and when the sum of the correction angles is positive. It is also used for leading load when the sum of the correction angles is negative.

Table II, having the same range as Table I, is to be used for leading load when the sum of the correction angles is positive and for lagging load when the sum of these angles is negative. In the cases where Table I is to be used, the wattmeter reads too high and the correction factors are less than unity, while under the conditions referred to in connection with Table II, the instrument reading is too small and the multiplier must be greater than unity.

Having discussed the reasons why the phase-angle and ratios of the instrument transformers must be known and what seems to be a convenient way in which the known corrections may be applied, we can by referring to the table easily see within what limits of accuracy and power-factor the correction for phase-angle may be neglected, and obtain a very good general idea of the effect of varying the power-factor of the circuit when any combined phase-angle is assumed.

In order to keep the error due to phase-angle within 1 per cent, if the sum of the correction angles is 30 minutes, correction must be applied after the power-factor becomes lower than 0.7. At power-factor 0.5 the error due to this cause would amount to about 1.5 per cent and at power-factor 0.1 to very nearly 9 per cent. To keep within the same 1 per cent limit, as low as power-factor 0.1, the sum of the correction angles must be under 5 minutes. It can also be seen that, within the limits where such corrections would ordinarily be useful, the multiplier to be used is very nearly proportional to the correction angle. The correction angle has no appreciable effect at unity power-factor up to the point where the angle exceeds, by a considerable amount, any magnitude which would usually be met with in practice. The tables have been extended to well beyond such limits.

Where the algebraic sum of the correction angles is greater than 90 degrees minus θ, the multipliers are not given, as they would not often be used. Under such conditions it would naturally be impossible to know how the reading of the instrument would be used without making some test by inserting reactance or capacity in the potential circuit of the wattmeter. By varying this reactance or capacity it is possible to observe whether the reading is due to the influence of the phase displacement in the transformers overpowering the action of the energy flowing in the circuit or whether the two forces are acting in the same direction on the instrument. This aspect of the question is referred to only to make it clear that such a condition may arise and that it has been considered. On the other hand, it is quite evident that no such condition could arise unless the power-factor of the circuit to be measured was extremely low or unless the sum of the correction angles was comparatively very large. This would mean that the correction factor would be so large that a very small error in the correction angle would render the results worthless.

The intention is not to discuss the design of current and potential transformers, but rather to consider the best means which may be employed to determine their corrections, and to apply the results of these tests to any measurements that may be made, with reasonable accuracy, using any given combined apparatus. Under some circumstances it is necessary, especially with current transformers, to determine the ratio and phase-angle by indirect methods, and as these indirect methods involve a general understanding of the theoretical elements of current transformers, this part of the subject will be dealt with only to the extent which is necessary. The potential transformer may not need such consideration in this place as the theory of transformers operating at constant potential has been much more fully dealt with. The current transformer has of course, received the attention of several writers, but these articles have in general been theoretical and have not been expanded in sufficient detail to be useful to those who require quantitative results.

The Current Transformer

The current circulating in the primary of the current transformer may be considered as consisting of two components, the current appearing in the secondary and the current necessary to excite the core. These two components are not usually combined in a straight line. In order to consider the relation between the exciting current, the primary and the secondary current, reference may be made to the diagram in Fig. 1. The magnitude of the exciting current is very small in comparison with the primary and the secondary currents, and therefore is not drawn to scale in the diagram. On account of the small

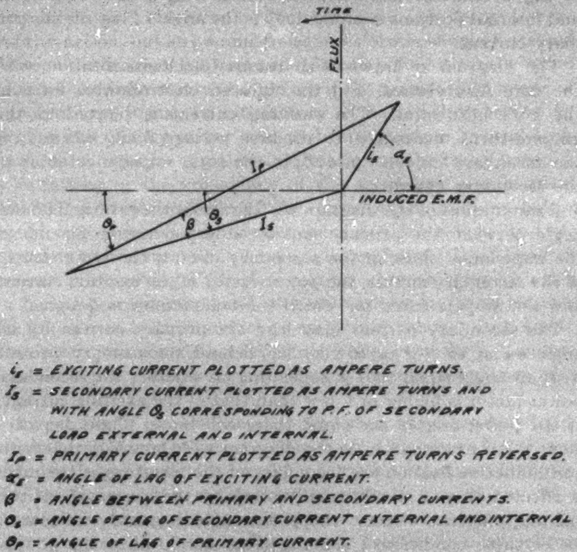
TIME
FLUX
I_p
i_e
a_e
INDUCED E.M.F.
θ_p
β
θ_s
I_s
i_e = EXCITING CURRENT PLOTTED AS AMPERE TURNS.
I_s = SECONDARY CURRENT PLOTTED AS AMPERE TURNS AND WITH ANGLE θ_s CORRESPONDING TO P.F. OF SECONDARY LOAD EXTERNAL AND INTERNAL.
I_p = PRIMARY CURRENT PLOTTED AS AMPERE TURNS REVERSED.
α_e = ANGLE OF LAG OF EXCITING CURRENT.
β = ANGLE BETWEEN PRIMARY AND SECONDARY CURRENTS.
θ_s = ANGLE OF LAG OF SECONDARY CURRENT EXTERNAL AND INTERNAL
θ_p = ANGLE OF LAG OF PRIMARY CURRENT.

Fig. 1.—Diagram of current transformer

relative value of the magnetizing current it is usually much more convenient and accurate to compute the ratio and phase-angle from the exciting current or to compute the exciting current from careful ratio and phase-angle tests, than it is to attempt to scale the diagram, although the diagram is useful as an aid in obtaining a clear conception of the operation of the transformer. In the diagram i_e is the exciting current plotted as ampere turns. I_s is the secondary current plotted as ampere-turns making an angle θ_s corresponding to the power-factor of the secondary load. This load consists of two parts: that external to the transformer, and that due to the resistance and reactance of the transformer secondary. The reactance of the secondary winding is inappreciable in any transformers that have been examined. I_p is the primary current plotted as ampere-turns reversed. α_s is the angle of lag of the exciting current; β is the angle between primary and secondary current; θ_s is the angle of lag in the secondary circuit considering both the external and internal portions combined; θ_p is the angle of lag of the primary current.

The diagram is drawn with counter clockwise rotation, with the core flux vertical and the induced electromotive force in the core horizontal. The exciting current is plotted as the ampere-turns necessary to produce voltage $I_s\ Z_s$ where I_s is the secondary current, and Z_s is the total impedance ohms in the secondary circuit.

Examination of the diagram will show that the ratio and phase-angle between the primary and secondary currents depend on the impedance ohms in the secondary circuit, the power-factor of the secondary circuit, the power-factor of the exciting current and the ampere-turns for which the transformer is designed.

The secondary current may lead the primary current by an angle equal to $+\beta$ or it may lag behind the primary current with an angle equal to $-\beta$ depending on whether the secondary power-factor is higher or lower than that of the exciting current. If the power-factors are equal there will be no phase displacement. An examination of the diagram will show also that with non-inductive load on the secondary of the transformer the ratio is affected to a relatively small extent by the magnitude of the exciting current, whereas the phase-angle is greatly influenced under these conditions. On the other hand, when the power-factor in the secondary circuit is lower and approximately that of the core, the exciting current is fully effective in varying the ratio of the transformer but has little effect on the phase-angle. With the information which we now have at hand it is possible to outline the tests which should be made on a current transformer in order that its performance under conditions of use may be known.

It is useful to know how the ratio and phase-angle are affected by variations in the frequency, in the line current, in the impedance of the secondary circuit, in the power-factor of the secondary circuit, or in the wave-form of the primary current. Small changes of frequency have little effect on the ratio. Tests made at 60 and 25 cycles will give sufficient data from which ratios, for intermediate cycles, can be readily obtained by interpolation when required.

Variations in line current affect the ratio of the transformer because the exciting current necessary to produce the required potential to force the secondary current through its circuit is not proportional to the current flowing with a given connected secondary load. Much can be done with a suitable design to control this action, but any commercial transformer should be tested between the limits of 0.1 load and full load before it can be relied upon for accurate measurements, or if the transformer is one of a general type it may be satisfactory to make a short test to determine the quality of the core and rely on more general tests on the same type for complete information on the transformer.

Variations in the impedance of the secondary circuit affect the ratio and phase-angle of the transformer, and, as before stated, the power-factor of the connected secondary load has a bearing on the ratio and phase-angle resulting. It is therefore necessary in making a complete test on a transformer, to test it on various power-factors, and with each power-factor to increase the impedance from minimum to maximum value. Such a test, however, consumes almost too much time, even for a standard test on a few transformers to obtain the characteristics of a type.

In practice it is quite usual to find that the secondary loads of small impedance have a comparatively high power-factor, and that the larger loads are usually of higher relative reactance. For this reason it is satisfactory to make a general test of a transformer, using the two frequencies above referred to, 25 and 60 cycles, and 5 loads which cover practically a range from a single instrument and a few feet of wire to a trip coil for the direct operation of an oil switch. For very accurate work it is sometimes useful to tabulate or draw a curve for another load in which there is no sensible impedance in the secondary circuit other than that offered by the secondary winding of the transformer itself. This zero load may be determined by interpolation from the tests made on the other loads and is chiefly of value when the transformer is to be used in connection with a single induction meter. The characteristics of these loads, which have been used in tests referred to later, are as follows:

All of the loads were tested using 5 amperes and 60 cycles, and any other load which is to be used on a transformer may be tested or computed by addition of the separate items, after being tested on the same basis. It has been found more convenient perhaps without good reason, to designate a given transformer load as a certain number of volt-amperes rather than to reduce it to resistance-reactance components unless the power-factor is quite different from that of the standard load with which it is to be compared.

	Amperes	Volts	Watts	Volt-amperes	Power-factor	Resistance	Ractance X 60 cycles
Load No. 1..........	5	2.104	8.32	10.52	0.79	0.3325	0.1578
Load No. 2..........	5	3.72	15.34	18.6	0.829	0.6168	0.4167
Load No. 3..........	5	4.98	16.06	24.9	0.645	0.6423	0.7615
Load No. 4..........	5	9.36	22.9	46.8	0.489	0.9155	1.6325
Load No. 5..........	5	27.5	49.09	137.5	0.357	1.964	5.140

These loads may be represented, in commercial instruments, about as follows:

Load No. 1, portable ammeter, portable wattmeter, and 50-ft. leads of No. 10 wire, (100 ft. of wire) or two station instruments and 15-ft. leads, or one station instrument and 200-ft. leads.

Load No. 2, same as load 1, with the addition of one station instrument or two portable instruments.

Load No. 3, two station instruments, relay, and 50-ft. loads.

Load No. 4, the maximum number of station instruments, up to four or five in number, in combination with a relay and leads.

Load No. 5, one coil, for directly tripping an oil switch in combination with ammeters and leads.

All the information given, covering the way in which the loads are made up, is only very approximate, and to determine the performance of any given transformer which has been tested on the above loads, definite knowledge should be had of the particular load on which it is to be used before the desired information can be obtained for the test records. The foregoing loads are only for use in testing transformers which have been designed for general switchboard requirements. Of course, transformers of smaller capacity, built for some special or specific use, will require testing only on the loads with which they are to be used.

There are many methods which may be employed to determine the ratio of current transformers. The most obvious one, and that which may be employed successfully, if a high degree of accuracy is not required, is to measure the primary and secondary current by means of any alternating-current ammeters which may be available. Unless some special equipment is available for measuring the primary current, and if this current is beyond the capacity of the comparatively small range of commercial instruments, the test finally resolves itself into a comparison between two current transformers, as a second transformer must be made use of, in connection with the primary ammeter. If a good, carefully checked, variable-ratio current transformer is available for the purpose, in combination with two good ammeters, the results obtained are quite satisfactory. It is not possible by this means accurately to determine the ratio down to a small primary current, say 10 per cent of maximum, which is required in connection with wattmeters.

It is not advisable to attempt to obtain lower current values, by using a smaller capacity instrument in the secondary, because of the change which this brings about in the impedance of the secondary circuit. If the transformer is a very good one, this change may result in a comparatively small error, but in such a transformer the difference in the value obtained at 10 per cent and, say, 25 per cent of primary current would be rather small. In general it is believed that if anything at all is known of the characteristics of the transformer, a closer approximation to the true ratio value at 0.1 load may be obtained by exterpolating the lower part of the curve than by attempting a measurement with small capacity instruments on the secondary.

Ratio determinations made with small-capacity ammeters have been used in connection with 5-ampere-capacity wattmeters, resulting in considerable error where a high degree of accuracy is required. Wattmeters give a better indication lower down on the scale than ammeters usually do, so that the temptation to use these instruments of small current capacity is not as great as with ammeters. However, if this is done not only is the ratio affected but the error due to phase-angle is usually increased. To illustrate this point still further, a portable 5-ampere ammeter requires about one volt to force through it full-capacity current, or 5 volt-amperes. A two-ampere instrument, having the same number of ampere-turns, requires 2.5 volts at 2 amperes, or for comparison with the 5-ampere instrument, 6.25 volts at 5 amperes, and acts on the transformer as a load equivalent to a little more than 36 volt-amperes, a load about half way between the number 3 and 4 loads which have been used in the tests.

If the transformers are to be used with the same instruments with which they are tested, of course instruments of any capacity or impedance may be included in the secondary circuit. This error has been made many times.

Even before the manufacture of current transformers was undertaken commercially, it was apparent that accurate ratio determinations under widely varying conditions required some special arrangement to do the work with a high enough degree of accuracy so that determinations could be made on transformers independent of their being combined with any specific instruments. As soon as work was started the fact also became apparent that the current transformer was a very accurate and reliable device. The effect of the exciting current is comparatively small, and may be varied within wide limits without affecting, except to a small degree, the ratio and phase-angle. The current transformer is by no means a perfect device, because it cannot give a constant ratio or phase-angle with change of primary current or secondary load. However, these errors may be reduced by careful design to almost any size, and if they have once been accurately determined they cannot change in any sensible amount, by reason of any changes which may occur in the exciting current due to variations in the core. This is assuming, of course, that the magnetic material of the core has been suitably chosen, and has received proper treatment so that it may remain permanent.

The following schemes for determining ratio and phase-angle have been tried with more or less success; they have all been satisfactory as far as accuracy goes, but with some of them the time required is at present too long to make it possible to use the methods in practical work.

METHOD OF DETERMINING RATIO AND PHASE-ANGLE BY REFLECTING DYNAMOMETERS

Referring to Fig. 2, the fixed coil of the primary dynamometer is connected in series with a shunt to the source of supply. The moving coil of the dynamometer is applied to the drop terminals of the shunt, and included in this potential circuit is the resistance r_p. Choosing suitable values for r_p and for the shunt resistance R_p, the combinations can be arranged to give a good deflection at from 0.1 to full rated primary current. The secondary is provided with a similar arrangement, usually of 5 amperes maximum capacity. In this circuit the energy to operate the combination must be limited. As usually arranged the secondary requires about 2 volts with full-load current of about 5 amperes, and is the No. 1 load referred to in the test.

The primary and secondary dynamometers are first carefully checked on direct current by means of a potentiometer. The test is then made and the ratio determined by dividing the primary current by the secondary current. In actual testing the primary current is brought up to the calibrated point and the secondary current is read. The scale reading obtained in calibrating the secondary dynamometer at the current corresponding to the correct ratio, is then divided by the reading obtained with the correct primary current, and the square root of the result is the accuracy of ratio. The instruments used

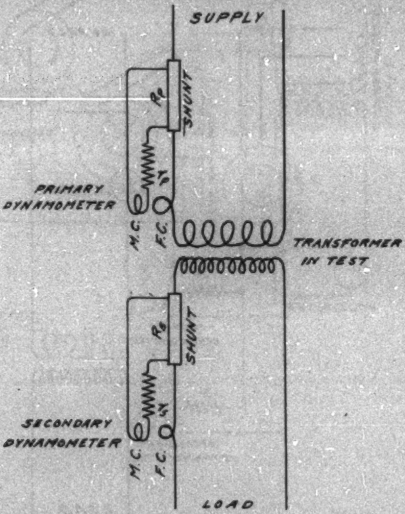

FIG. 2.—Connections for ratio test on current transformer by two dynamometer method

measure the watts lost in the shunt resistance, and, therefore, give a deflection proportional to the current squared. It has been found more convenient to express this ratio as that of a 1:1 transformer, or to write the true ratio divided by the marked ratio, than to use the actual ratio of transformation, as by this means transformers of the same type may be directly compared although their current capacity is quite different. In common with any other method in which the primary and secondary currents are actually measured and used to compute the ratio of the transformers, this method would not appear at first sight to be satisfactory from the standpoint of either accuracy or speed. It depends, of course, entirely on the accuracy which may be secured with the instruments used. The results obtained in this way have been more satisfactory, so far, than by any other method. In Fig. 3, connections are shown for determining the phase-angle between the primary and secondary

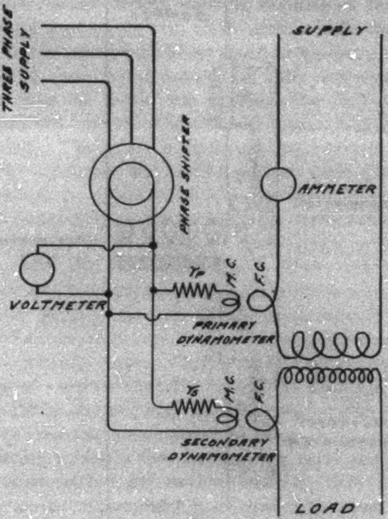
THREE PHASE SUPPLY
SUPPLY
PHASE SHIFTER
AMMETER
VOLTMETER
r_p
M.C
F.C
PRIMARY DYNAMOMETER
r_s
M.C
F.C
SECONDARY DYNAMOMETER
LOAD

FIG. 3.—Connections for phase-angle test on current transformer by two-dynamometer method

currents. Dynamometers are the same as used for the ratio determination as in Fig. 2. The current windings are in the primary and secondary as before, but the current-carrying resistances are not necessary except to keep the secondary load unchanged. The potential coils of the instrument are connected to a phase-shifter, shown in the diagram, this phase-shifter being rotated until the primary dynamometer reads zero. The phase-angle then is,

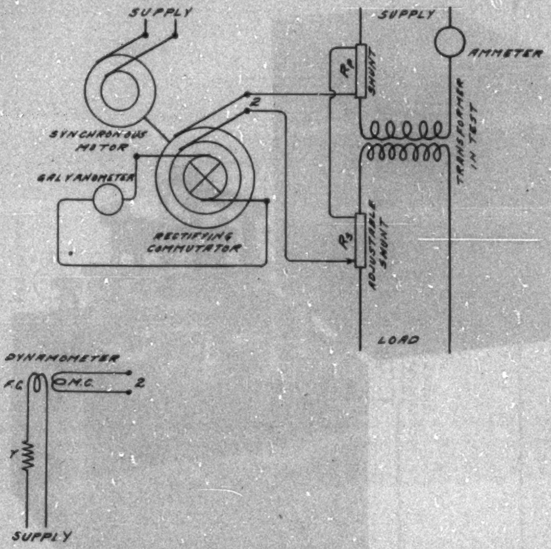
SUPPLY
SYNCHRONOUS MOTOR
2
GALVANOMETER
RECTIFYING COMMUTATOR
SUPPLY
AMMETER
R_2
SHUNT
TRANSFORMER IN TEST
R_3
ADJUSTABLE SHUNT
LOAD
DYNAMOMETER
F.C.
M.C.
2
r
SUPPLY

Fig. 4.—Connections for ratio test on current transformer by comparison of resistances, using dynamometer or rectifying commutator and galvanometer

$$\beta = \sin^{-1} \frac{W_s}{I_s \times E}$$

where I_s is the secondary current in the transformer, as before,

W_s is the watts read on the dynamometer and E is the voltage on the phase-shifter, at the point where the potential coil is attached. It is worth while mentioning here that to secure accurate results the resistances r_p and r_s must be practically perfect and without inductance or capacity, and if the moving coils have appreciable inductance the L/r of the circuits must be equal. In the actual tests referred to it has been found best to make the inductance of the moving coil practically zero.

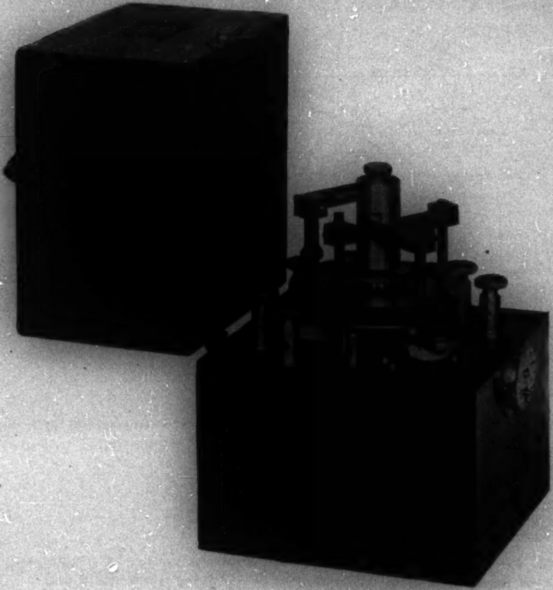

FIG. 5.—Rectifying commutator

Referring to Fig. 4, suitable non-inductive resistances or shunts, one fixed and one adjustable, are included in the primary and secondary circuits. After connecting as shown in the figure, it is only necessary to make use of some form of sensitive alternating-current galvanometer to show when the potential drop on the two shunts balances. The secondary shunt is adjusted until this balance is secured, then the ratio equals $\frac{R_s}{R_p}$. The equality of potential can be shown by a rectifying commutator in combination with a direct-current galvanometer, or by using the moving coil of one of the reflecting dynamometers, the fixed coil of which is energized from any convenient point of the same circuit. Fig. 5 shows a rectifying commutator driven by a synchronous motor, which has been developed for this use.

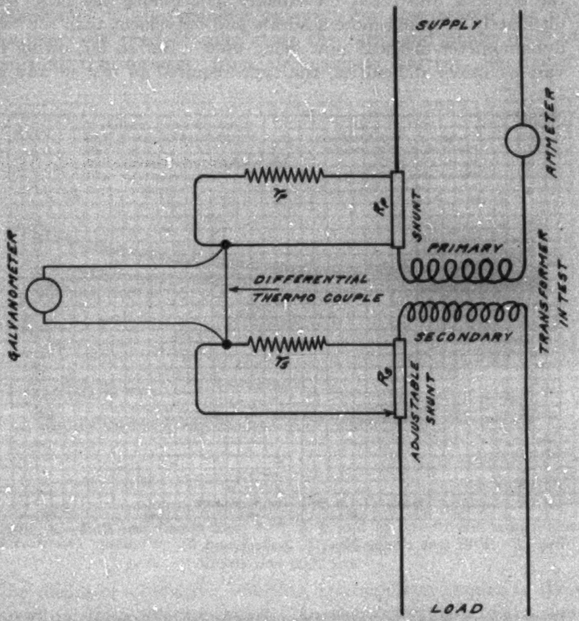
SUPPLY
AMMETER
r_p
R_p
SHUNT
PRIMARY
TRANSFORMER IN TEST
GALVANOMETER
DIFFERENTIAL THERMO COUPLE
SECONDARY
r_s
R_s
ADJUSTABLE SHUNT
LOAD

Fig. 6.—Connections for ratio test on current transformer by comparison of resistances, using differential thermo-couple and galvanometer

Fig. 6 shows another way of determining the ratio by means of current-carrying resistances and an alternating-current comparator of any suitable type. The expansion comparator of Dr. Northrup has been used for this method, and also a thermo comparator, as shown in the figure. The experiment of using a differential dynamometer has also been tried, but without any very satisfactory results. It is hoped that one of the schemes illustrated for directly determining the ratio will ultimately be found more accurate and convenient than the two dynamometer methods now being used. But so far, owing to various minor difficulties, the time required to test in any of these direct ways is much longer, and the accuracy is no better than that obtained by using the first method in Fig. 2.

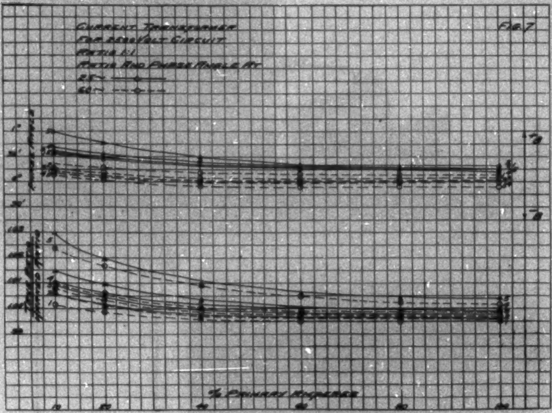

FIG. 7.—Full test (loads Nos. 1, 2, 3, 4 and 5) on current transformer for 2500 volt circuit

In order to show the general character of the tests as outlined, and to bring out clearly the fact that tests made by the method referred to in connection with Figs. 2 and 3 are satisfactory, as far as accuracy of results is concerned, two complete tests are shown in Figs. 7 and 8. It will be seen that the observed points lie very closely on the smooth curves. It can also be seen that the observations must be made with considerable precision, else the curves cannot be plotted with sufficient accuracy to be clearly read. This is especially true of the phase-angle tests.

It is possible to extend the capacity of the methods referred to up to any required current value; but with either the dynamometer or shunt methods great difficulties are encountered in producing instruments or shunts of very large capacities in which the eddy currents or other disturbing causes have been eliminated to the required extent. For this reason the expedient was tried of calculating the ratio and phase-angle of current transformers, from the exciting current determined

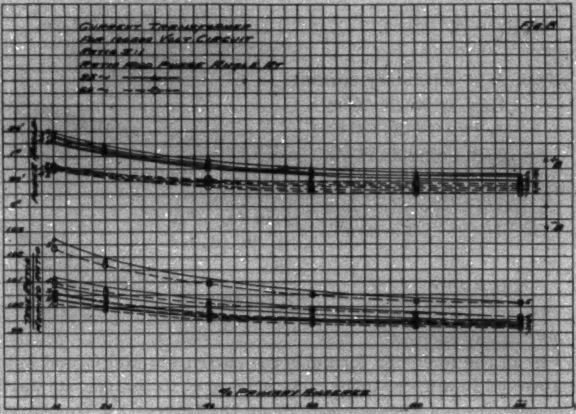

Fig. 8.—Full test (loads Nos. 1, 2, 3, 4 and 5) on current transformer for 100,000 volt circuit

by means of a sensitive reflecting dynamometer similar to those used for ratio determinations. Another instrument of the same class was used for determining the watts lost in the core. From the indications of these instruments may be plotted exciting current against volts produced on the secondary of the transformer and a second curve of volts and power-factor. From these the amount and apparent angle of the exciting current can be read for use in calculating the ratio and phase-angle. From the transformer diagram in Fig. 1, the following expressions for ratio and phase-angle can be obtained in terms of the exciting ampere-turns:

Ratio =

$$\frac{I_p}{\sqrt{(I_p \cos \theta_p - i_e \cos \alpha_e)^2 + (I_p \sin \theta_p - i_e \sin \alpha_e)^2}}$$

where I_p = primary current in ampere-turns
θ_p = its angle of lag
i_e = exciting current in ampere-turns
α_e = its angle of lag.

As the calculations are usually made on the basis of given conditions in the secondary circuit we can write

$$\text{Ratio} = \sqrt{\frac{(I_s \cos \theta_s + i_e \cos \alpha_e)^2 + (I_s \sin \theta_s + i_e \sin \alpha_e)^2}{I_s}}$$

where I_s = secondary current
θ_s = its angle of lag
i_e = exciting current
α_e = its angle of lag

and for phase-angle

$$\beta = \tan^{-1} \frac{i_e \sin (\alpha_e - \theta_s)}{I_s + i_e \cos (\alpha_e - \theta_s)}$$

or

$$\beta = \sin^{-1} \frac{i_e \sin (\alpha_e - \theta_s)}{I_p}$$

In all the foregoing formulas the currents i_e and I_p and I_s are expressed in ampere-turns. As it is usual to compensate partly for the effect of exciting current on the ratio of the transformer by winding the secondary of a transformer with a few turns less than the primary turns times the marked ratio, this fact must not be overlooked in the calculations, and the actual number of secondary turns must be used. In certain cases it may be useful to work out, for comparison, exciting-current values from tests on ratio and phase-angle to compare tested points with those obtained by calculation. For this purpose we can write,

$$i_e = I_s \sqrt{R^2 - 2R \cos \beta + 1}$$

$$\sin (\alpha_e - \theta_s) = \frac{I_p \sin \beta}{i_e}$$

Of course, only a rough idea of the exciting current values can be obtained in this way, but when it is pointed out that an 0.1-per cent error in a ratio determination may easily cause 10 per cent error in the exciting current determined in this way, the explanation is sufficient.

The computer should not be misled by the fact that an exciting-current curve may frequently be computed back in this way, and pass evenly through all the points.. This would simply indicate that a smooth curve had been drawn through the ratio determinations and accurately read before being introduced in the calculations.

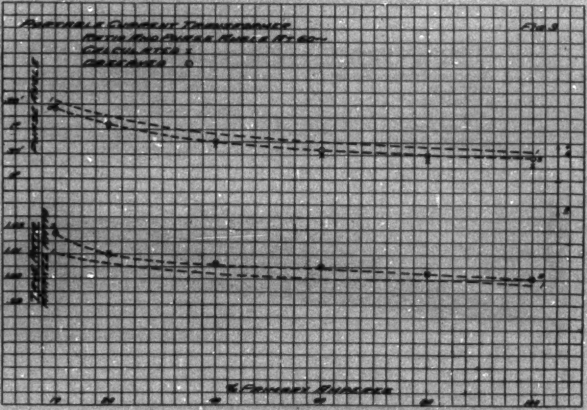

Fig. 9.—Comparison between observed and calculated ratio and phase angle on portable variable ratio current transformer

In Fig. 9 are shown ratio and phase-angle determinations on a portable transformer for variable ratio; in this transformer the primary winding is wound in by the user to meet the immediate requirements. This test was made on 60 cycles, using No. 3 load. The calculated and observed points have all been plotted. From this it can be seen that the calculated values agree with the observations well within the limits of accuracy expected. The phase-angle values have also been computed and are shown in the same way. The agreement here is also satisfactory and the method can be applied to transformers of any capacity. The reason for choosing the portable transformer of comparatively small ampere capacity in preference to a large bus-bar transformer, is the difficulty in determining the large primary current by methods that would be above suspicion.

THE POTENTIAL TRANSFORMER

The same general considerations which apply to current transformers may be expanded to cover the potential transformers. As before stated this will not be done at the present time, both because the subject has received more general attention, and because the determinations of the ratio and phase-angle, even with comparatively high primary voltages, are much easier to make than similar tests on the current transformers. It is possible, using the apparatus about to be described and without a prohibitive expenditure of time, to test a potential transformer on any frequency with the secondary loaded from a single high-resistance instrument up to its maximum rated capacity. If convenient means are at hand it is also possible to determine quickly by test the ratio and phase-angle when the power-factor of the connected secondary load varies between any desired limits. Such a complete test is

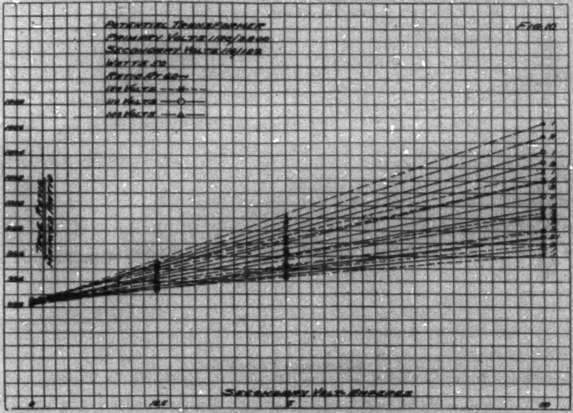

Fig. 10.—Full test of ratio on potential transformer

shown in Figs. 10 and 11. Various methods have been used for this work, as well as for current-transformer testing, but the one finally chosen has been found so convenient and accurate that no other special device will be referred to in connection with the testing of potential transformers.

Referring to Fig. 12, and to Figs. 13, 14 and 15, a complete equipment is shown there, especially constructed to produce transformer tests of the general kind shown in Figs. 10 and 11. This is suitable for use on any frequency and up to 33,000 volts. Additional resistance may be coupled to the standard arrangement, so that the range may be temporarily extended to any desired limit. The resistances r_1 and r_2 are connected across the primary circuit with taps for various voltages, so that about 10 ohms per volt may be used. The primary and secondary are connected together and to the ground as shown. The polarity is such that the potential rise from ground along the secondary of the transformer is in the same direction as that from ground along the main primary resistance. Then a point may be found in the primary resistance which is at the same potential as the high side of the secondary. We then have,

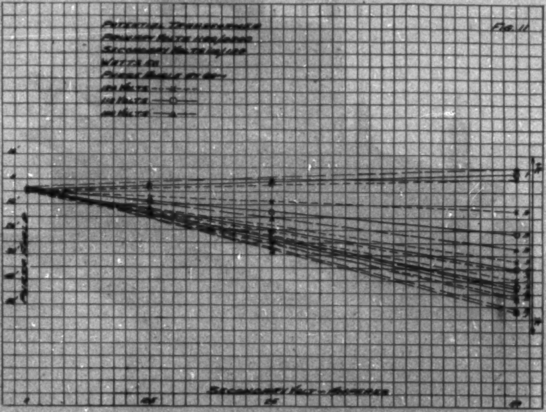

Fig. 11.—Full test of phase angle on potential transformer

$$\text{Ratio} = \frac{r_1 + r_2}{r_2}$$

The equality of potential is determined by a dynamometer, referred to in Fig. 4, or by a synchronous commutator, as shown in Fig. 13. The apparatus is made direct reading to within 0.1 per cent between the limits of 5 per cent below and 5 per cent above the marked ratio of any transformer, by employing the 100-point switch shown in Fig. 12. The movable contact, by which the potential coil of the dynamometer is moved along the primary high resistance, may be advanced by 1-ohm steps. Arranged in this way the ratio observations can be made as rapidly as they can be recorded, and values may be interpolated to 0.01 per cent if desired. The arrangements

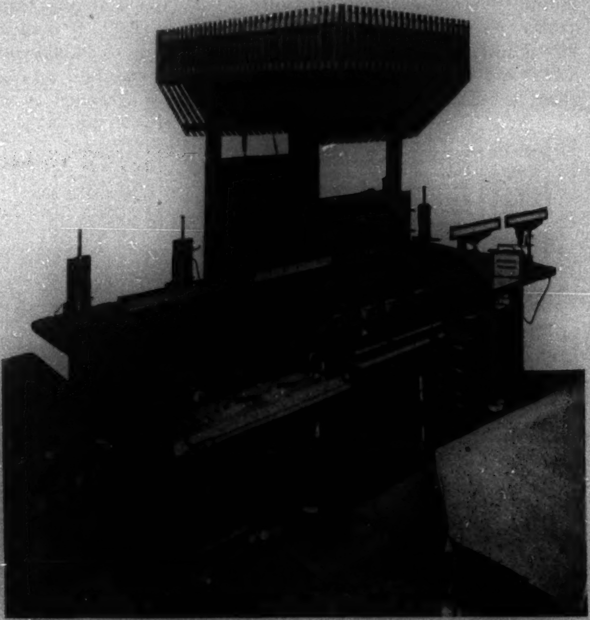

FIG. 12.—Outfit for ratio and phase angle test on potential transformers referred to in Fig. 8

provided for loading the transformers are shown in Fig. 15. Reactances are provided taking about 0.12 ampere at 110 volts and 60 cycles, and having a power-factor of about 10 per cent, together with another set of reactances taking about 0.15 ampere at 25 cycles and having about the same power-factor. These may be combined in various ways so that the reactance load at low power-factor may be put on the transformers up to about 2 amperes. Resistance load, variable by much finer

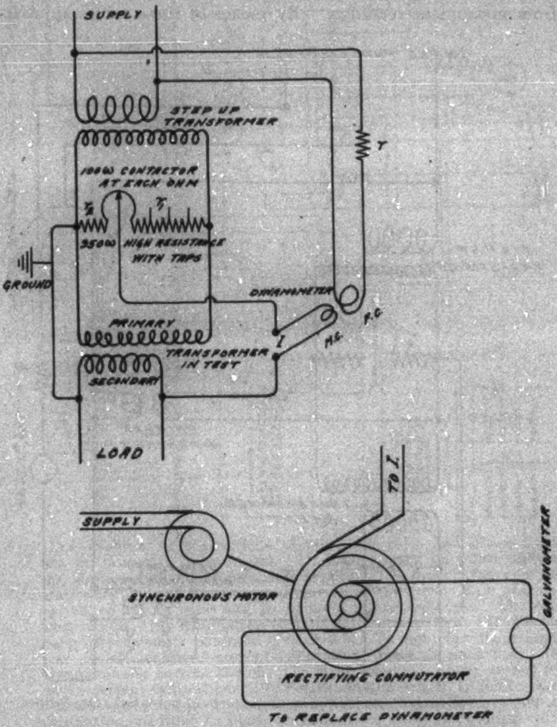
SUPPLY
STEP UP TRANSFORMER
T
100Ω CONTACTOR AT EACH OHM
r_2
r_1
350Ω HIGH RESISTANCE WITH TAPS
GROUND
DYNAMOMETER
F.C.
M.C.
I
PRIMARY
TRANSFORMER IN TEST
SECONDARY
LOAD
TO I
SUPPLY
SYNCHRONOUS MOTOR
GALVANOMETER
RECTIFYING COMMUTATOR
TO REPLACE DYNAMOMETER

FIG. 13.—Connections for ratio test on potential transformer

steps, is also available up to the same ampere capacity. By combining these in suitable ways the desired load at any power-factor can be accurately obtained between the limits of 0.1 power-factor and unity. To avoid the time required to make adjustment of load, tables have been prepared by computations from instrument readings. By means of these tables approximately any ampere load at a definite power-factor can be arranged at once. It is not important to have the load in amperes very exact, as the lines connecting the observed points are practically straight, but the power-factor must be accurately adjusted to plot as shown in Figs. 10 and 11.

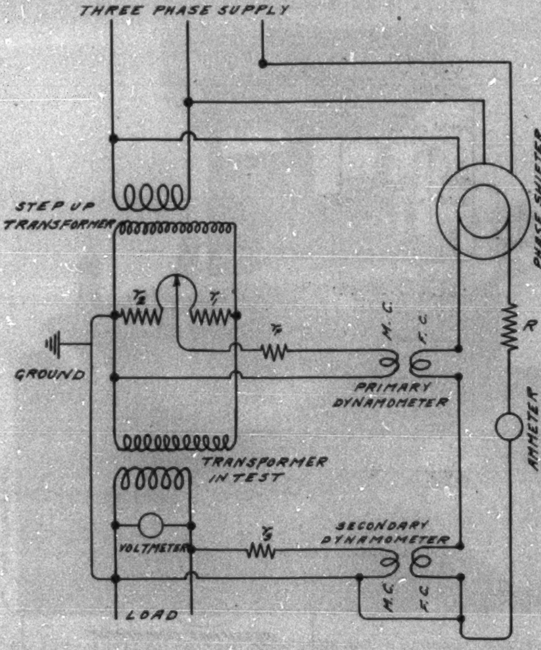
THREE PHASE SUPPLY
STEP UP TRANSFORMER
PHASE SHIFTER
r_2
r_1
r_p
M.C.
F.C.
R
GROUND
PRIMARY DYNAMOMETER
AMMETER
TRANSFORMER IN TEST
VOLTMETER
r_s
SECONDARY DYNAMOMETER
M.C.
F.C.
LOAD

FIG. 14.—Connections for phase angle test on potential transformer

The phase-angle is determined on the potential transformers

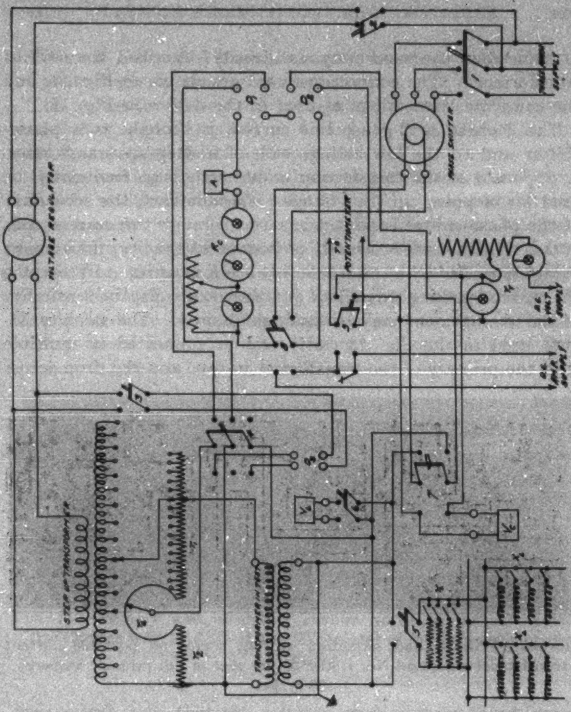
VOLTAGE REGULATOR
PHASE SHIFTER
TRANSFORMER SUPPLY
TO POTENTIOMETER
A
R_c
D_1
D_2
D_3
D.C. VOLT. SUPPLY
A.C. AMP. SUPPLY
1
2
3
4
5
6
7
8
9
V_l
V_c
r_1
r_2
x_1
STEP UP TRANSFORMER
TRANSFORMER

FIG. 15.—Diagram of connections of outfit for ratio and phase angle test on potential transformers. (1) Main switch on phase shifter. (2) Main switch on transformer supply. (3) Switch for exciting stationary coils of dynamometer for ratio test. (4) Main transfer switch; to left for ratio test, to right for phase angle test. (5) Main load switch. (6) Alternating-current voltmeter switch. (7) Secondary dynamometer potential coil switch. To right for phase angle test, to left for direct-current calibration, open for ratio test. (8) Dynamometer current switch. To right for phase angle, to left for direct-current calibration. (9) Potentiometer switch; to left to place potentiometer leads in series with direct-current for wattmeter calibration; to right to place potentiometer leads in multiple with direct-current voltmeter for calibration. r_1 high resistance with taps. r_2 950 ohms. r_a 100 ohms in 1 ohms steps for adjustment of moving contact. r_1 resistances to furnish load for secondary. x_1 reactance coils to furnish load for secondary. V_l alternating current voltmeter. V_c direct-current voltmeter for calibration. r_v resistances to regulate voltage applied in calibration. R_c resistances for control of current (alternating current or direct-current) applied to dynamometers. D_1, D_2 dynamometers with suitable resistances in series with potential circuits for determining phase angle. D_3 dynamometer with suitable resistances in series for ratio test.

in somewhat the same way as already described for current transformers. The connections used are shown in Fig. 14, and the complete connections as used in the device in Fig. 15.

The 3-phase or 2-phase line current is brought to a phase-shifter and to the low-voltage side of a step-up transformer. A duplicate of the transformer under test may frequently be used for stepping up the voltage. Current from the secondary of the phase-shifter is passed in series through the current coils of two dynamometers, usually of 5-ampere capacity, the amount being controlled by a suitable resistance R in series. By varying the current passing through R and the fixed coils, the sensibility of the arrangement may be made as desired. The same resistance used in the Fig. 13, ratio test, is connected in multiple with the primary of the transformer in test, and the drop across a considerable portion of it is used to excite the moving coil of the primary dynamometer. The resistances r_p, r_1, r_2, and r_s must be practically perfect, as in phase-angle testing of current transformers. The secondary voltage of the transformer under test is used to excite the potential coil of the secondary dynamometer through the resistance r_s. The current coil and the potential coil on the secondary dynamometer must be connected together, as shown. The load on the transformer under test is then adjusted to the proper current and power-factor, and the phase is shifted until the primary dynamometer reads zero. The phase-angle between the primary and secondary electromotive force is then,

FIG. 16.—Primary and secondary current waves on portable current transformer with load No. 1, and 25 per cent of full primary amperes, 60 cycles

$$\gamma = \sin^{-1} \frac{W_s}{E \times A}$$

Where W_s, E and A have the same meaning as in the formula for phase-angle on the current transformer.

The voltmeter V, is used to regulate the test voltage on a transformer, and if it is left on during the test, it must be considered as part of the transformer load.

Before leaving the general subject of instrument transformers it may be well to refer to one point about which some uncertainty exists; namely, the effect of current transformers in causing a wave to appear in the secondary circuit, differing in form from that of the primary. As the shortest and most satisfactory way of disposing of this point, oscillograph records, Figs. 16, 17 and 18 have been taken, showing primary and secondary current waves in a current transformer. Examination of these figures will show that the primary wave is reproduced, practically unchanged, in the secondary. A much distorted wave was purposely chosen.

Fig. 17.—Primary and secondary current wave on portable current transformer with load No. 1 and 50 per cent of full primary amperes, 60 cycles

Conclusions

For measuring large alternating currents and voltages, current and potential transformers must usually be employed. If these are carefully designed they may be used with small errors resulting with various devices connected in the secondary circuit, and with primary current varying between the limits of the connected instrument scales, also with voltage and frequency variation usually met with in practice. If some care is not used in selecting suitable apparatus to meet conditions, errors as great as 5 or 10 per cent or more may occur. If the transformers are constructed with special reference to handling a given load, the errors may be limited to almost any required amount. To meet conditions of testing where low power-factor is present, or where a high degree of accuracy must be attained, carefully determined corrections for ratio and phase-angle must be applied. Such corrections, once determined for any given transformer, are permanent, and by their use the transformers may be considered precision instruments.

Wattmeters, when used without current or potential transformers, may be made to give indications correct within the limits of error of observation down to a power-factor as low as 10 or 15 per cent. Under certain conditions which may occur in practical work, it is well to know and apply corrections to the instruments themselves. If the conditions are such that the wattmeter must be corrected for phase-angle to insure suitable accuracy, current and potential transformers should not be used, unless the conditions are somewhat favorable and the corrections for the transformers are determined and applied with great care.

Fig. 18.—Primary and secondary current waves on portable current transformer with load No. 1 and 100 per cent primary amperes 60 cycles

In presenting the foregoing on the use of instruments in connection with current and potential transformers, it is perhaps proper to say that a considerable part of the subject matter contained therein has received more or less complete treatment in various publications. An incomplete list of such articles is here given. The paper should be considered as an attempt to describe, with enough detail to be of practical use, some specific methods of determining and applying corrections to the results obtained. The methods have been selected, after several years experience, as being best suited to the requirements that had to be met from time to time.

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The Use of Shunts and Transformers with Alternating-Current Measuring Instruments, Chas. V. Drysdale, D. Sc. Philosophical Magazine, Vol. XXI, July, 1908.

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The Theory and Use of the Alternating-Current Wattmeter, Chas. V. Drysdale, B. Sc., London Electrician, Vol. XLVL, March 15, 1901, page 775.

Precautions to be Observed in Applying Corrections to Wattmeter Readings, Ernst Danielson, *Electrical World*, Vol. XLX, No. 10, March 5, 1892.

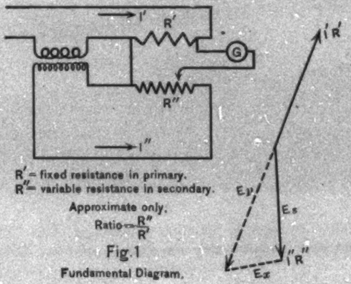
The Measurement of Phase Differences, Chas. V. Drysdale, D. Sc., London Electrician, Vol. 57, Aug. 24, 1906, page 726. August 31, 1906, page 783.

DISCUSSION ON "ELECTRICAL MEASUREMENTS ON CIRCUITS REQUIRING CURRENT AND POTENTIAL TRANSFORMERS." FRONTENAC, N. Y., JUNE 30, 1909

C. H. Sharp: This important question of the measurement of ratio and phase-angle of transformers is beginning to receive the attention it deserves. I should like to call attention to similar work done at the Electrical Testing Laboratories under my direction by Wm. W. Crawford.

By the two-ammeter method of measuring the ratio of current transformers, it is possible to get quite accurate results, but their accuracy is limited by the steadiness of the available alternating-current supply. It is also desirable that the two instruments should have as nearly as possible the same natural frequency of oscillation.

Being dissatisfied with the results obtained by the two-ammeter method, we sought a method which would be free from its disadvantages, and two years ago worked out the two-shunt method outlined by Mr. Robinson. This is essentially a bridge or zero method in which the fluctuations of the supply do not go into the result directly, and which has also the great advantage of giving the result in terms of the ratio of two resistances. We have developed also the shortcomings of this method, which are described below, and have devised means whereby they might be overcome and also a scheme for measuring the phase-angle of the transformer at the same time that its ratio of transformation is obtained.



R' = fixed resistance in primary.
R'' = variable resistance in secondary.
Approximate only.
Ratio $= \frac{R''}{R'}$

Fig. 1
Fundamental Diagram.

The simple connection shown in Fig. 4 of Mr. Robinson's paper does not give a wholly exact value for the ratio of the transformers, for the reason that the primary and secondary currents are not in phase with each other and their phase-angle increases with decreased load. Referring to Fig. 1, we have e_p the fall of potential on the primary shunt, e_s that on the secondary shunt, and e_x the reactive potential difference which is present even when $e_p = e_s$ numerically. Now, if the rotating commutator is adjusted so that its axis of commutation bisects the angle between e_p and e_s, the galvanometer measures the difference between the projection of e_p on the axis of commutation, and of e_s on the same axis. When the deflection of the galvanometer is reduced to zero by adjusting the secondary shunt, the ratio of shunt resistances gives very accurately the ratio of the transformer. The difficulty is to set the axis of commutation to approximately the right position. If this axis of commutation falls some distance outside the angle made by e_p and e_s, the ratio measured will be incorrect.

To obviate this difficulty, the reactive potential difference e_x must be nullified. The first method used for this purpose is illustrated in Fig. 2. In this method a fixed non-inductive resistance R'' is introduced into the secondary circuit, and this is shunted by a potentiometer arrangement R_s of 100 ohms, in series with which is a variable standard of self-induction L by means of which the current through R_s may be brought into phase with that through R'.

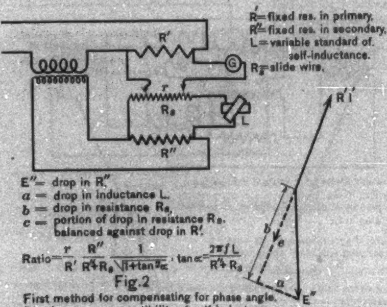

R′ = fixed res. in primary.
R″ = fixed res. in secondary.
L = variable standard of. self-inductance.
Rs = slide wire.
R′
G
r
Rs
L
R″
R′I′
b
e
a
E″
E″ = drop in R″.
a = drop in inductance L.
b = drop in resistance Rs,
c = portion of drop in resistance Rs. balanced against drop in R′.
Ratio = r/R′ · R″/(R″+Rs) · 1/√(1+tan²α) · tan α = 2πfL/(R″+Rs)

Fig. 2

First method for compensating for phase angle. Disadvantage:-susceptibility of self-inductance to stray field effects.

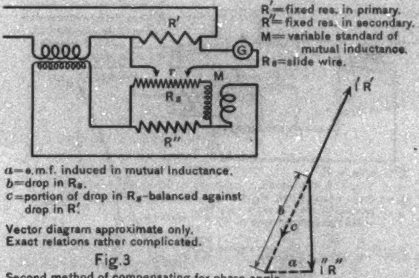
The procedure then is as follows: the axis of commutation is brought as nearly as possible into the general direction of the vectors of the fall of potential of primary and secondary shunts, by noticing the position of the commutator which gives the maximum sensibility to the arrangement; that is, the position in which a given change in the secondary shunt throws the apparatus farthest out of balance. Having determined this position, and having adjusted R_s so that the galvanometer deflection is zero, the line of commutation is rotated through an angle of 90 deg. At this point the sensitiveness of the arrangement in measuring the inductive difference e_x is the maximum, and the deflection here observed is brought to zero by adjusting the value of the self-induction L. This operates to bring the potential differences on the shunts substantially into phase with each other.

When this has been accomplished, the brush holder is rotated back into its original position and the adjustment of R_s is again made. The second value of R_s so found must be almost exactly correct since it is made when e_p and e_s are in phase with each other, and consequently the ratio of their projections upon any line gives the true ratio of the potential differences. The ratio of the transformer is then given by the expression:

$$\text{Ratio of transformation} = \frac{r}{R'} \quad \frac{R''}{R''+R_s} \quad \frac{1}{\sqrt{1+\tan^2 \alpha}}$$

where α, the phase-angle of the transformer is given by the relation,

$$\tan \alpha = \frac{2 \pi f L}{R''+R_s} \cdot$$


R'
r
M
G
R_s
R''
R'=fixed res. in primary.
R''=fixed res. in secondary.
M=variable standard of mutual inductance.
R_s=slide wire.
I'R'
b
c
a
I''R''
a=e.m.f. induced in mutual inductance.
b=drop in R_s.
c=portion of drop in R_s-balanced against drop in R'.

Vector diagram approximate only.
Exact relations rather complicated.

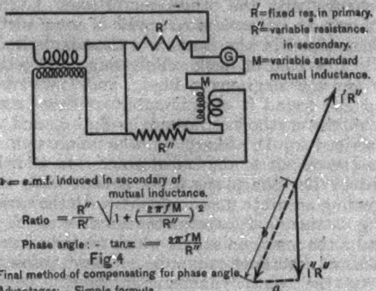
Fig.3

Second method of compensating for phase angle.
Disadvantage:- complicated formula.

The principal disadvantage of this method is that the ordinary Ayrton-Perry form of standard of self-induction is such that it is subject to influence by stray alternating fields, and a very feeble stray field would in the case of these measurements be sufficient to destroy the accuracy of the measurements. It is evident that in the foregoing work, not only has the ratio of the transformer been determined, but at the same time the phase-angle between primary and secondary currents has been measured.

Following this, a second method, shown in Fig. 3, was developed in which a variable standard mutual-induction was substituted for the variable standard of self-induction, and since a standard of mutual-induction can be made astatic so as not to be influenced by stray fields, this difficulty of the first method was overcome. The relations involved in applying this second method are rather complicated, and as a result the method has been abandoned for one illustrated in Fig. 4, in which the arrangement of circuits was suggested by Mr. F. K. Vreeland. As will be seen, the primary of the mutual-inductance is in series with the secondary of the transformer, while the secondary of this mutual-inductance is connected in series with the galvanometer. The operations are exactly as described in the first method but the formula is even more simple than in that method, while the trouble from stray field is avoided by using an astatic mutual-inductance.

The methods here given have the advantage over Mr. Robinson's method of not requiring two wattmeters which are accurate on low power-factors, together with a voltmeter and ammeter, three observers, and a steady current. By this method not only is the true ratio of the transformer obtained as a ratio of resistances, but the phase-angle is measured by actually nullifying the reactive potential difference which corresponds to it. With the exception of an ammeter to show approximately what the load is, no direct-reading instruments are required.



R' = fixed res. in primary.
R'' = variable resistance in secondary.
M = variable standard mutual inductance.

a = e.m.f. induced in secondary of mutual inductance.

$$\text{Ratio} = \frac{R''}{R'}\sqrt{1 + \left(\frac{2\pi f M}{R''}\right)^2}$$

$$\text{Phase angle:} - \tan x = \frac{2\pi f M}{R''}$$

Fig. 4

Final method of compensating for phase angle.

Advantages: - Simple formula.
Less susceptibility to stray fields.
Greater sensitiveness.

Moreover, the arrangement is independent of sensitive suspended instruments. It is quite feasible to use a resistance of very small fall of potential for the primary and secondary shunts and still have sensitiveness enough even when a pivoted direct-current galvanometer is used. On account of the character of the apparatus employed, it is possible by one of these methods to measure the ratio of a transformer installed on a switchboard and to do it with a high degree of accuracy. This at once extends the range of possibilities of this sort of testing beyond the walls of the laboratory—a very important consideration in many instances.

We have found that the rectifying commutator in the form in which Mr. Robinson describes it is not a success. As soon as the current becomes very small the contact resistance of brush with commutator is very uncertain, sometimes reaching a high value. We have obviated this difficulty by substituting a vibrating rectifying device operated by a cam on the shaft of the motor. Straight pressure contact instead of rubbing contact is thereby obtained, and operates satisfactorily. The primary non-inductive shunts for this sort of work present very serious problems of construction as soon as heavy currents have to be dealt with, and they must be arranged to be cooled by some liquid.

A similar method can be used for the measurement of the ratio of potential transformers. As a current detector an alternating-current—direct-current voltmeter can be used, provided its connections are changed so that its field coils can be separately excited. For most purposes the sensitiveness of such an instrument is sufficient. The methods and apparatus for carrying them out as described in the foregoing have been developed in the Electrical Testing Laboratories quite independently of any similar work done elsewhere.

M. G. Lloyd: Mr. Robinson's table and diagrams will no doubt be useful as showing the general way in which those quantities change with the conditions of load.

I think it may be of interest to speak of some methods that have been developed at the Bureau of Standards and are now being used in this kind of work. Referring first to the current transformer and the diagrams in Figs. 2 and 3: we tried out the first method and found it objectionable, at least not quite as serviceable as the method indicated in Fig. 4, and similar to the one described by Dr. Sharp, in which only two shunts are necessary in the circuit of the transformer. In addition to the points raised by Dr. Sharp, one other is that while there is no trouble in getting accurate measurements with the arrangements shown in Fig. 2, since a dynamometer must be in the secondary circuit, it limits the load conditions which must be used; that is, the resistance and reactance cannot be cut down below the values necessary for the watt-dynamometer itself. Consequently, the secondary circuit cannot be made as small as it might be in practice, and therefore as small as it would be desirable to have the conditions in calibrating.

The alternative diagram in the lower left-hand corner of Fig. 4, is a method that we have found of more service. At the terminals 2, we connected one coil of the dynamometer; the other coil had current supplied to it in phase with the primary of the transformer. The result is that the potentials across the two resistances, R_p and R_s are opposite and not exactly in phase, their resultant being a small voltage in quadrature, and the dynamometer is made to read zero. In the case of any good transformer the ratio of resistances gives the ratio of the currents since the cosine of the small angle is a negligible factor.

We have found it simpler to obtain the phase-angle measurement almost simultaneously by using a somewhat different scheme. Instead of using a three-phase supply we have tried using a two-phase source of supply, and we have found that preferable. Using a two-phase supply we have a second dynamometer whose field is supplied with current in quadrature; we then apply the same electromotive force, which represents the difference in the drop in the two shunts, R_p and R_s, to the other coil of the dynamometer having its field in quadrature. The deflection, then, measures a small quantity which, in ratio to the primary potential drop, gives the phase-angle of the transformer; so that by a simple throwing of the switch the second measurement is obtained.

The method with the mutual inductance, mentioned by Dr. Sharp, I believe is the same as that used at the National Physical Laboratory, in England, and described in their last annual report.

In regard to potential transformers, our method is very similar to that used by Mr. Robinson; that is, we balance a fractional part of the potential of the primary against the potential of the secondary. I need not speak of that in detail; suffice it to say that here again in obtaining the phase-angle we use the quadrature current as the auxiliary instead of the phase-shifting transformer, with the result that by simply throwing the same difference of potential on the second dynamometer, that quantity is measured directly and gives the phase-angle. These methods which we have finally found the most preferable were given several months ago in a paper read before another society.*

As Mr. Robinson has pointed out, the transformer is an instrument of precision when used under proper conditions. There is one way, however, in which an error may be introduced even when the transformer has been calibrated and when it is not subject to such errors as aging. That is due to the fact that iron requires a different magnetizing current in some cases from what it needs in others. Such a case can be brought about by magnetizing highly in one direction and then subsequently breaking the magnetizing current. It will be then in a condition that is not neutral. If that operation is performed with the current transformer, and its ratio then measured, it will be found that the ratio will not be of the same value as when the iron is in a neutral condition.† That does not apply to a potential transformer, because there the magnetizing current comes in only as a second-order effect. In the current transformer, where the ratio is thrown off from the nominal value entirely by the exciting current, this effect comes in very strongly and may produce an appreciable error.

Hence when calibrating the current transformer and using it afterwards, one should be sure that a definite condition of the iron exists. That can be arranged by putting the core through a demagnetizing process before using it. Such an abnormal condition may easily result, because if the secondary happens to be open-circuited we have the condition spoken of. The magnetism of the core jumps to a high point and if the flux is suddenly cut down by closing the secondary, it is brought down without the demagnetizing process.

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* Agnew and Fitch, *Phys. Rev.* 28, p. 473; June, 1909.

† Attention was first called to this by Agnew and Fitch loc. cit.

In regard to which angle should be called positive and which negative, I wish to take issue with Mr. Robinson. The point mentioned earlier, depending upon whether we shall call a lagging angle positive or negative, I will not go into because that is a point which depends largely upon the way in which one has been trained. But coming to the specific case of designating these angles, it seems to me that the method used in this paper is inconsistent and undesirable. It will be noticed in the case of the current transformer that when the secondary leads, the angle is called positive, and in the case of the potential transformer it is called negative. There is an inconsistency between the two cases. The reason for doing this is to make it possible to take the sum of the two angles and determine the apparent power-factor. It seems to me that is confusing. Anyone understands that if the current and the potential are thrown off simultaneously in the same direction; that is, if each one is caused to lag by the same number of degrees, the reading of the wattmeter will not be altered. The first thing that naturally occurs to one is that the difference of the two phase-angles must be taken. So it would be more logical and less confusing to call the phase-angle positive in one definite direction, preferably when the secondary leads.

In the formula on the fourth page, I would suggest that having indicated which angles are positive and which negative, it would be better to omit the combined sign plus and minus and let it stand as plus.

In an early part of the paper, under the things to be investigated, Mr. Robinson has mentioned the effect of wave-form. I think he takes up all the other points, but he says nothing further about this. Over a year ago I published an article* giving some experiments on that point. The results showed that with any distortion that would be likely to be present on an ordinary circuit, the ratio is not affected. There is a small effect with very large distortion. In a book by Arnold,† this section of which was written by LaCour, there is a theoretical discussion on this subject, based on the assumption that harmonics can affect the result only by their value and regardless of their phase. In other words, if the same harmonics are in such phase as to produce a flat wave and a peak wave, the result should be the same. This is not in agreement with the experimental facts.

L. W. Chubb: I would like to ask if the transformers giving the curves shown in Figs. 7 and 8 were of special design for the test, or whether they were commercial transformers, and what were the load conditions 1, 2, 3, 4, and 5?

I would also like to ask Dr. Sharp if the extra circuit containing the resistance and inductance as shown in his diagram would take enough current to prohibit getting any desired conditions of instrument load during a test?

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* *Electrical World* 52, p. 845, 1908. *Bull. Bur. Stds.* 6, No. 1, 1909.

† Wechselstromtechnik, Vol. 1, p. 254.

Albert F. Ganz: I wish to ask Mr. Robinson whether he has any method to suggest for measuring the phase-angle α in the wattmeter itself, also whether in a properly designed transformer, β is not always positive and γ negative? Is there anything about the tests that will enable one to tell whether these angles are positive or negative?

C. H. Sharp: Answering Mr. Chubb's question: in this method of testing current transformers the high relative sensibility of direct-current galvanometers can be utilized. Consequently it is not necessary that the fall of potential in these shunts should be large. As a practical matter we work with one-quarter of an ohm in the secondary circuit of the transformer, but we could just as well use two-tenths or one-tenth. The inductance is entirely negligible.

L. T. Robinson: In reply to Dr. Sharp, I would say that it is not necessary to take into account the small error due to the fact that the primary and secondary currents are not exactly in phase. I think that the somewhat elaborate arrangements which he has shown are an entirely unnecessary refinement. By reference to a table of cosines it will be seen that if the transformer is reasonably good; that is, if the angles are nearly as they should be, it will be entirely beyond the accuracy wanted in a commercial test. If the angle β is as much as 2 deg. the necessary correction (sec $\beta - 1$) amounts to only about 0.05 per cent. If desired, correction can easily be made for this small angle, but if a transformer were brought to me for test, and I had to take this correction into account, I would not make a complete test. The transformer would evidently not be a good one.

I think that the method suggested for measuring the phase-angle is very ingenious. I have not had the time to try it but my opinion is that it would not allow a determination to be made with the same degree of precision that could be obtained by using the method given in the paper.

The question was raised as to the number of observers and the time required to complete the work. I would say frankly that I expected better results with the resistance methods that have been described, and the only reason I can give for not having adopted long ago for commercial work what will no doubt prove to be the final method is, that where one has so much to do it is difficult always to bring into daily use methods which promise to be better. I am quite willing to say, however, that from my point of view the length of time for these tests is quite satisfactory.

The commutator I myself do not like. We did try it and it will work, but I think I would prefer some other method.

Dr. Lloyd referred to Figs. 2 and 4. I prefer Fig. 4 unless some arrangement like that shown in Fig. 6 can be used. I believe this will be the ultimate outcome.

It is true that the secondary load conditions are limited by the dynamometers. From my own point of view this is no objection, because we can go to the limits of the smallest connected load that it would ever be necessary to use, and there is no use in going further. For precision work we would not use a transformer with less on it than one portable ammeter and one portable wattmeter, and the combined load of these two is just about equal to what we can easily get by the methods we have used.

As to the effect of the altered magnetizing current due to the previous state of the core affecting the ratio, I would say that this fact has been appreciated for some time. I thought it was so well known that I did not need to refer to it. All users of current transformers have for some time been cautioned against leaving the secondary circuit open.

M. G. Lloyd: The same effect is brought about if the dynamometer is calibrated with the secondary or primary in circuit with direct current.

L. T. Robinson: I know that, but we do not do it.

As to the angles and sines, I appreciate this fact, that it may not be logical and I do not offer it as such; but after one has carefully selected the best method and no one else is doing the same thing at that time, the only way is to proceed and afterward tell how it was done and what one's opinion of it is. I am perfectly willing to make a change if we can come to any satisfactory understanding about what it is best to do.

In reply to Mr. Chubb's question as to the loads used: I described their properties though perhaps not in sufficient detail. The loads are given in electrical terms and below is given a brief description of the actual loads used.

The tests of transformers were all made on commercial specimens. Professor Ganz asked how to determine the angle α. I would say that one cannot tell everything in a single paper. I shall be glad to tell him privately what we do.

J. Dalemont (by letter): I wish to call attention to the influence of the core-loss and magnetic leakage upon current transformers. I have recently made some measurements on two current transformers having iron cores of the same cross-section and nearly the same length, but of different form: one as in Fig. 1, the other as indicated in Fig. 2.

On one of the legs of the prismatic core, the following sets of coils were mounted in succession:

$$1\begin{cases}\text{Primary;} & 5 \text{ turns.}\\ \text{Secondary;} & 460 \text{ turns.}\end{cases}\qquad 2\begin{cases}\text{Primary;} & 41 \text{ turns.}\\ \text{Secondary;} & 460 \text{ turns.}\end{cases}$$

The transformer was supplied with an alternating current of almost sine shape and a frequency of 36 cycles. On the torus core, a secondary winding of 460 turns was wound uniformly. The primary wire carrying the current was placed in the direction of the axis of the torus, perpendicular to the plane of the paper and was supplied with the same current as before. The secondary circuits were closed on standard ammeters. Table I gives the values of the primary and secondary currents in each case.

It will be seen that in the first case (ratio of 5 to 460, prismatic core), the average of the primary and the secondary currents is 83.4, while the ratio of the number of turns is 92; with the other coils (ratio 41 to 460) on the same core, the average ratio of the currents is 12.2, while the ratio of the turns is only 11.2.

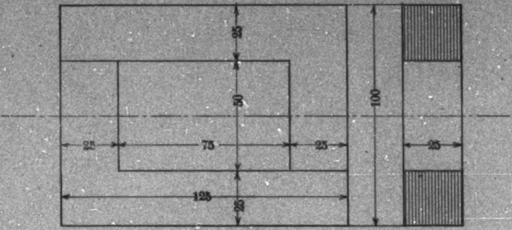

FIG. 1

Taking the relation between the ampere-turns, we have:

$$\frac{n_2\, I_2}{n_1\, I_1} = \frac{4\, \pi\, n_2\, p}{\sqrt{R^2\, r_2^2 + (4\, \pi\, n_2^2 + l_2\, R)^2\, p^2}}$$

where p is the frequency,

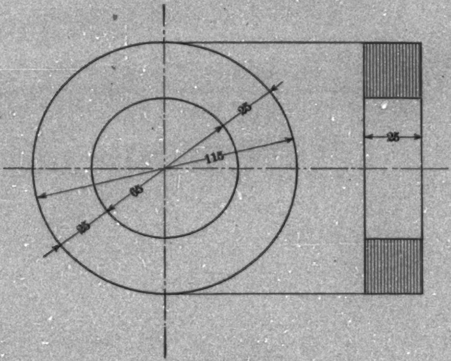

FIG. 2

R = the magnetic reluctance of the core.

r and $p\, l$, the resistance and the reactance of the secondary circuit.

It will be seen that this ratio is equal to 1 when the losses are negligible.

TABLE I

Ratio $\frac{5}{460}$		Ratio $\frac{41}{460}$		Ratio $\frac{1}{460}$	
Core 1		Core 1		Core 2	
I_1 ampere	I_2 ampere	I_1 ampere	I_2 ampere	I_1 ampere	I_2 ampere
93	1.09	15.5	1.23	567	1.15
116	1.37	19.8	1.58	755	1.58
135.2	1.61	23.4	1.89	936	2
150	1.79	27.7	2.23	1021	2.18
170	2.03	32.3	2.62	1098	2.32
184	2.19	35.8	2.91	1175	2.52
205	2.45	39.2	3.17	1265	2.68
233.3	2.77			1355	2.87
263	3.13			1495	3.17
275	3.25			1670	3.54
299	3.53			1772	3.77

TABLE II

Curve 1		Curve 2		Curve 3	
$n_2 I_2$	$\frac{n_1 I_1}{n_2 I_2} - 1$	$n_2 I_2$	$\frac{n_1 I_1}{n_2 I_2} - 1$	$n_2 I_2$	$\frac{n_1 I_1}{n_2 I_2} - 1$
502	−.073	565	.122	529	.048
632	−.082	727	.115	727	.036
742	−.088	870	.102	920	.020
825	−.092	1025	.098	1000	.024
936	−.093	1205	.100	1068	.032
1008	−.088	1339	.095	1160	.030
1130	−.092	1458	.095	1232	.028
1275	−.087			1320	.026
1440	−.086			1958	.025
1498	−.082			1628	.025
1625	−.080			1732	.022

The curves in Fig. 3 show the variation of the ratio

$$\frac{I_1 n_1 - I_2 n_2}{I_2 n_2}$$

plotted to $I_2 n_2$ as abscissas. The advantage of the torus form for the magnetic core is thus clearly demonstrated by these results. On the other hand, a rectangular section for the magnetic core is preferable to a square section, but with the low values of induction used in such apparatus (2750 c. g. s.), the difference is very small. For a comparison of the two cores from this point of view, the numerical values of the above expression are given in Table II.

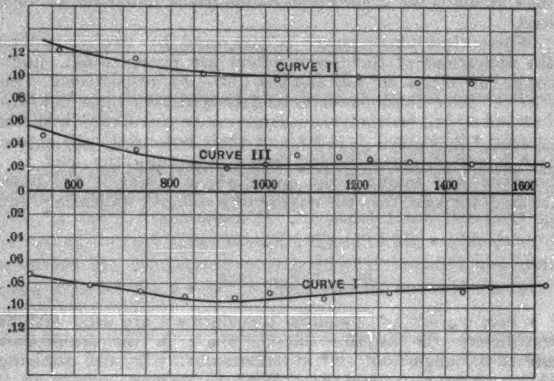

FIG. 3

Albert F. Ganz (by letter): Mr. Robinson shows that where a wattmeter is used with current and potential transformers, the wattmeter reading must be multiplied by the factor

$$\frac{\cos \theta}{\cos [\theta - (\alpha + \beta + \gamma)]}$$

in order to correct for the error due to phase displacement between current and voltage caused by the wattmeter itself, and by the transformers where

θ = phase angle between current and voltage in the main circuit assumed *positive* when the current is *lagging.*

α = equivalent angle of phase displacement between current in the potential coil and voltage across the potential terminals of the wattmeter, assumed *positive* when the current *lags* behind this voltage.

β = angle of phase difference between the primary and the secondary current in the current transformer, assumed *positive* when the secondary current *leads* the primary current reversed.

γ = angle of phase difference between the primary and the secondary voltage in the potential transformer, assumed *positive*, when the secondary voltage *lags* behind the primary voltage reversed.

Mr. Robinson has also given convenient tables of correction-factors for various power-factors of the load, and for phase displacements up to 5 degrees. The correction-factor as given by the above formula, and the tables as given by Mr. Robinson, are directly applicable to a single-phase circuit, in which case θ of the formula is the angle whose cosine is the power-factor of the load.

Where three-phase power is measured by two wattmeters, the indications of these wattmeters are proportional, not to cos θ, but to $\cos(30° + \theta)$ and $\cos(30° - \theta)$, respectively. Suppose the three-phase power to be delivered over three line wires, 1, 2 and 3, and let the two wattmeters be connected with their current coils in lines 1 and 3 and their potential coils across 1 and 2, and 3 and 2, respectively. Assuming the load to be balanced, and taking θ the angle whose cosine is the power-factor of the load, then the wattmeters will give indications equal to

$$P_1 = E\,I\cos(30° - \theta),$$

and

$$P_3 = E\,I\cos(30° + \theta).$$

Where current and potential transformers are used with two wattmeters, the displacement of phase in the transformers affects the angle $(30° - \theta)$ in wattmeter #1, and the angle $(30° + \theta)$ in wattmeter #3. With a lagging current in the load—that is, with θ positive—P_3 will be the smaller wattmeter reading and P_1 the larger wattmeter reading.

To correct for phase displacement, the reading of wattmeter #1 must be multiplied by

$$\frac{\cos(30° - \theta)}{\cos[30° - \theta + (\alpha + \beta + \gamma)]},$$

and that of wattmeter #3 must be multiplied by

$$\frac{\cos(30° + \theta)}{\cos[30° + \theta - (\alpha + \beta + \gamma)]}.$$

In applying Mr. Robinson's tables to three-phase power measured by two wattmeters, the θ used in the tables must be taken equal to 30 degrees minus the angle whose cosine is the power-factor of the load, for wattmeter reading #1; and equal to 30 degrees plus the angle whose cosine is the power-factor of the load, for wattmeter reading #3.

A paper presented at the 26th annual convention of the American Institute of Electrical Engineers. Frontenac, N. Y., June 30, 1909.

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ELECTROMOTIVE FORCE WAVE-SHAPE IN ALTERNATORS

BY COMFORT A. ADAMS

The method of connecting the shape of the flux distribution curve of a synchronous converter with the shape of its induced electromotive force wave, developed by the writer in his Atlantic City paper,* is here applied more specifically to the alternator, with an illustration taken from Mr. Bache-Wiig's Atlantic City paper on the "Application of Fractional Pitch Windings to Alternating-Current Generators." Parts of the explanation of the *method* are reproduced in a somewhat modified and condensed form for the benefit of those who did not read the other paper.

The shape of the electromotive force wave of an alternator at no load is in general dependent upon the shape of the flux distribution curve and upon the arrangement of the armature conductors. But when the slots are large as compared with the air-gap, there is a pulsation of the flux in both magnitude and position,† which may materially alter the shape of the electromotive force wave. In the case of modern alternators with good inherent regulation, the air-gap is usually so long that these tooth pulsations are negligible; they will therefore not be considered here. The long gap and stiff field also tend to minimize the distortional effect of the armature magnetomotive force and to maintain a more nearly constant wave-shape at all loads.

With these reservations it will be assumed that a single conductor or a bundle of conductors placed in a single slot, will experience an electromotive force the wave-shape of which is the same as that of the flux distribution curve.

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* "Voltage Ratio in Synchronous Converters, with Special Reference to the Split Pole Converter." A. I. E. E. June, 1908.

† "Magnetic Pulsation in Alternators." Worrall. I. E. E. Jan. 1908

The electromotive force of one phase of an alternator is ordinarily made up of several of these slot electromotive forces added together in their proper phase relation, the electromotive forces of two adjacent slots being displaced by an angle corresponding to the slot pitch. If each slot electromotive force were sinusoidal the addition could be readily accomplished, but as this is not usually the case, the problem is not quite so simple. The method here employed is as follows:

Analyze the flux distribution curve into its fundamental and its various harmonics.

Make a vector addition of the fundamentals of the proper slot electromotive forces to obtain the fundamental of the phase electromotive force.

Make a vector addition of the mth harmonic of the proper slot electromotive forces to obtain the mth harmonic of the phase electromotive force.

Add the phase fundamental to the several phase harmonics to obtain the complete phase electromotive force.

Unless it is desired actually to plot the resultant wave, the last step is not necessary, since for all purposes of calculation the harmonics are treated separately.

TYPES OF ARMATURE WINDING

In order properly to carry out the above-mentioned vector additions, it will be necessary to consider the possible relative locations of the coil-sides which go to make up a given phase of the winding.

For the present purpose alternator armature windings may be classified as follows:

a. According to the angular span of a single phase belt. In the ordinary three-phase alternator this is 60 degrees, and as the three-phase machine is so nearly exclusively employed at the present time, the following discussion will refer thereto unless otherwise specified.

b. According to the number of slots per pole. Although this quantity can have almost any value, the more common values are small multiples of the number of phases, and these common values will be here considered unless otherwise specified.

c. According to the " pitch," " span " or " throw " of the coils.

The coil pitch is usually equal to or less than the pole pitch. Fig. 1 shows a simple two-layer winding with a full-pitch winding, six slots in six. Fig. 2 shows the same winding except that the coil pitch is reduced to four slots in six, or 66⅔ per cent. In this two-layer type of winding the pitch may be any whole number of slots, without destroying the mechanical symmetry.

d. According to the number of coil sides per slot. The two-layer winding shown in Figs. 1 and 2 has two coil-sides per slot, but a somewhat equivalent winding may be made with one coil-side per slot, see Fig. 3. With this one-layer winding, however, mechanical symmetry demands a coil pitch which, when measured in slots, is odd. In Fig. 4 is shown a similar one-layer winding, but with nine slots per pole; here there is a dissymmetry of coil connection, in that the alternate groups of coils in a given phase contain numbers of coils differing by one. This will be found to hold in this type of winding whenever the number of slots per pole is odd, 9, 15, 21, etc.

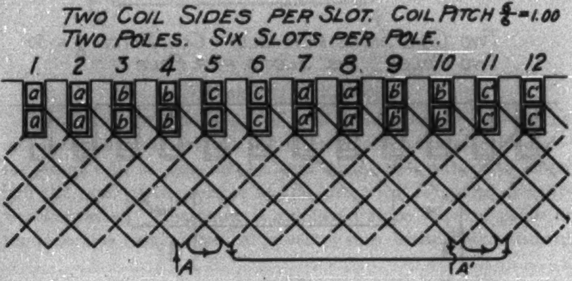
TWO COIL SIDES PER SLOT. COIL PITCH $\frac{6}{6}$=1.00
TWO POLES. SIX SLOTS PER POLE.
1
2
3
4
5
6
7
8
9
10
11
12
a
a
b
b
c
c
a'
a'
b'
b'
c'
c'
a
a
b
b
c
c
a'
a'
b'
b'
c'
c'
A
A'

FIG. 1

There are other very common types of alternator armature windings, but for the purpose in hand they are for the most part equivalent to those already described.

In each type of winding shown there are two groups of coils per phase per pair of poles, and these are shown connected together between the terminals, *A* and *A′*. In each case except that of Fig. 4 the two groups thus connected are exactly similar. Each group of coils is in turn made up of two similar groups of coil-sides or phase *belts*. In Fig. 1 one of these belts comprises the two coil-sides in the tops of slots No. 1 and No. 2, and the other includes the two coil-sides in the bottoms of slots No. 7 and No. 8. These two belts make up one of the similar coil-groups above referred to, the electromotive force of which has the same shape as that of the whole phase. In Fig. 1 the two belts in question are displaced by six slots or 180 degrees (electrical), and as they are connected in circuit opposition their electromotive forces are exactly in phase. Thus the electromotive force of one of these belts is a sample of the whole phase electromotive force.

In Fig. 2, however, the second belt (in the bottom of slots No. 4 and No. 5) is displaced from the first by only three slots, or 90 degrees, and the two belt electromotive forces differ in phase by 180 degrees − 90 degrees = 90 degrees, which is the pitch deficiency of the coils, measured in electrical degrees. In this case the electromotive force of the coil-group has the same shape as that of the whole phase-circuit, but in general not the same shape as that of a single belt.

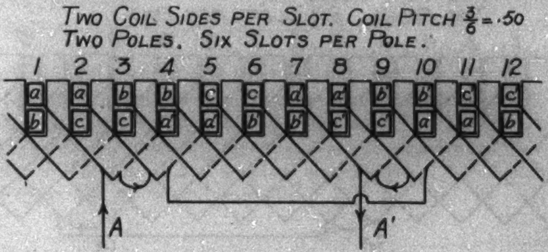
TWO COIL SIDES PER SLOT. COIL PITCH 3/6 = .50
TWO POLES. SIX SLOTS PER POLE.
1
2
3
4
5
6
7
8
9
10
11
12
a
a
b
b
c
c
a'
a'
b'
b'
c'
c'
b
c
c
a'
a'
b'
b'
c'
c'
a
a
b
A
A'

FIG. 2

In Fig. 3 the belt, which in Fig. 2 is distributed in the tops of slots No. 1 and No. 2, is all in slot No. 1. Had there been four slots per pole per phase, this belt would have been distributed in the tops of slots numbers 1, 2, 3 and 4 in the type of Fig. 2, but in the type of Figure 3 would be found concentrated in slots No. 1 and No. 3. There would be a similar change in the distribution of the other belts.

In Fig. 4 the two adjacent coil groups in a given phase are not similar since they contain different numbers of coils, and it takes both of these groups as connected between *A* and *A'* to make a sample unit as far as the electromotive force wave-shape is concerned. It will be observed in this connection that the phase of the electromotive force of the coil 11–16 is half way between that of coil 1-6 and that of coil 3-8. Thus the shape of the electromotive force wave is exactly the same as that of a two-layer winding with the same number (3) of slots per pole per phase. This relation obviously holds for the one-layer winding whenever the number of slots per pole per phase is odd.

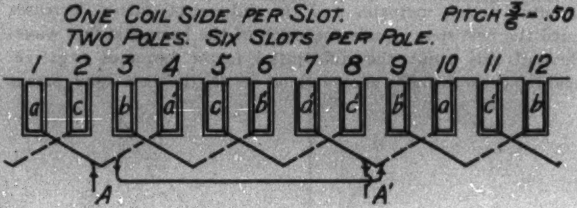
ONE COIL SIDE PER SLOT.
PITCH 3/6 = .50
TWO POLES. SIX SLOTS PER POLE.
1 2 3 4 5 6 7 8 9 10 11 12
a c b a c b a c b a c b
A
A'

Fig. 3

Differential Factor

In the vector additions of the fundamentals or of the *m*th harmonics of several slot electromotive forces, the vector sum will in general be less than the numerical sum, and the ratio of the former to the latter will be called the *differential-factor*. This name is employed since the real cause of the reduction from numerical to vector sum is the distribution of the winding and the resulting *differential* cutting of flux by the conductors in the several slots of a given phase belt; that is, there are times when some of these slots are cutting positive flux while others in the same belt are cutting negative flux. This differential action is not considerable when the phase belt is narrow as compared with the half wave of flux distribution. For example, in an ordinary three-phase alternator with a belt

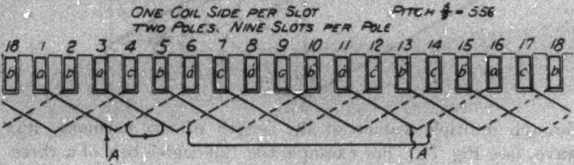
ONE COIL SIDE PER SLOT
PITCH 5/9 = .556
TWO POLES. NINE SLOTS PER POLE
18 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
b a b a c b a c a c b a c b c b a c b
A
A'

Fig. 4

60 degrees wide the differential factor for the fundamental flux wave is about 0.96, depending somewhat upon the number of slots per pole; but when this 60-degree belt is considered as cutting the third harmonic flux distribution, the half wave of which spans only 60 degrees, it is obvious that the differential action is much greater. As the belt becomes relatively broader with respect to the length of the harmonic flux wave, the differential action increases and the differential factor decreases until the belt span equals the pitch of the harmonic flux wave. Beyond this point the differential factor becomes negative, again passes through zero and so on as the belt span passes

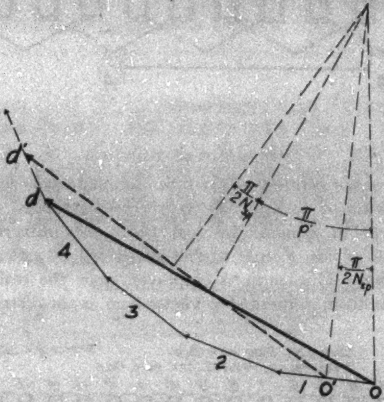

FIG. 5

through multiple values of the length of the harmonic flux wave, (see Fig. 7). For example the 120-degree belt of a three-phase converter, or the two adjacent 60-degree belts connected in series between the terminals of a star-connected alternator, would span 360 degrees of the third harmonic flux wave, 3×360 degrees of the ninth, 5×360 degrees of the fifteenth, and so on, the differential factor being zero in each case. That is, these harmonics disappear. Thus although the differential action reduces the fundamental electromotive force, it reduces most of the harmonics to a much greater extent, and tends to make the belt electromotive force more nearly sinusoidal than the slot electromotive force or flux distribution curve.

The effect of a fractional pitch winding is to introduce still further differential action between the two belts which go to make up one coil group, the amount of which depends upon the coil pitch and the harmonic in question.

Belt Differential Factor. Consider first the differential action within a single belt for the case of a two-layer winding. Figs. 5 and 6 show the vector relations of the fundamentals, and the third and the fifth harmonics for a three-phase machine with 12 slots per pole.

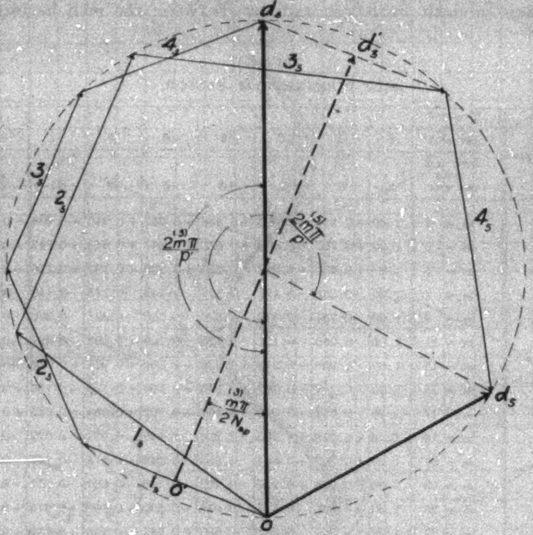

FIG. 6

In Fig. 5, the vectors 1, 2, 3 and 4 represent the four fundamental slot electromotive forces of one phase belt and $\overline{o\,d}$ their resultant. In Fig. 6 the vectors 1_3, 2_3, 3_3 and 4_3 represent the four third harmonic slot electromotive forces of one phase belt and $o\,d_3$ their resultant. Similarly 1_5, 2_5, 3_5 and 4_5 represent the corresponding fifth harmonic slot electromotive forces and $o\,d_5$ their resultant.

Let N_{sp} = slots per pole, and
p' = the number of belt spans per pair of poles, ($p' = 6$ for ordinary three phase).

Then $\frac{\pi}{N_{sp}}$ = the phase difference between the fundamental electromotive forces of two adjacent slots, $\frac{m\pi}{N_{sp}}$ = the phase difference (in mth harmonic radians) between the mth harmonic electromotive forces of two adjacent slots, $\frac{2N_{sp}}{p'}$ = slots per belt, and $\frac{2m\pi}{p'}$ = the total belt span in mth harmonic radians.

TABLE I

BELT DIFFERENTIAL FACTOR

N_{sp}	One coil side per slot	6	12	18	24	30	36	42	48
	Two coil sides per slot	3	6	9	12	15	18	21	24
	$m = 1$	1.00	+0.966	+0.960	+0.958	+0.957	+0.956	+0.956	+0.956
	$m = 3$	1.00	+0.707	+0.667	+0.653	+0.647	+0.644	+0.642	+0.641
	$m = 5$	1.00	+0.259	+0.218	+0.205	+0.200	+0.197	+0.196	+0.194
	$m = 7$	1.00	−0.259	−0.177	−0.157	−0.149	−0.145	−0.143	−0.141
	$m = 9$	1.00	−0.707	−0.333	−0.270	−0.248	−0.236	−0.229	−0.225
	$m = 11$	1.00	−0.966	−0.177	−0.128	−0.109	−0.102	−0.097	−0.095
	$m = 13$	1.00	−0.966	+0.218	+0.128	+0.102	+0.091	+0.086	+0.083
	$m = 15$	1.00	−0.707	+0.667	+0.270	+0.200	+0.173	+0.159	+0.149
	$m = 17$	1.00	−0.259	+0.960	+0.157	+0.102	+0.084	+0.075	+0.070
	$m = 19$	1.00	+0.259	+0.960	−0.205	−0.109	−0.084	−0.072	−0.066
	$m = 21$	1.00	+0.707	+0.667	−0.653	−0.248	−0.173	−0.147	−0.127
	$m = 23$	1.00	+0.966	+0.218	−0.958	−0.149	−0.091	−0.072	−0.063
	$m = 25$	1.00	+0.966	−0.177	−0.958	+0.200	+0.102	+0.075	+0.063
	$m = 27$	1.00	+0.707	−0.333	−0.653	+0.647	+0.236	+0.159	+0.127

If the diagram (Fig. 6) be reduced to unit radius, the resultant of the $\frac{2N_{sp}}{p'}$ mth harmonics will be $2 \sin \frac{m\pi}{p'}$. On the same basis the mth harmonic of the slot electromotive force is

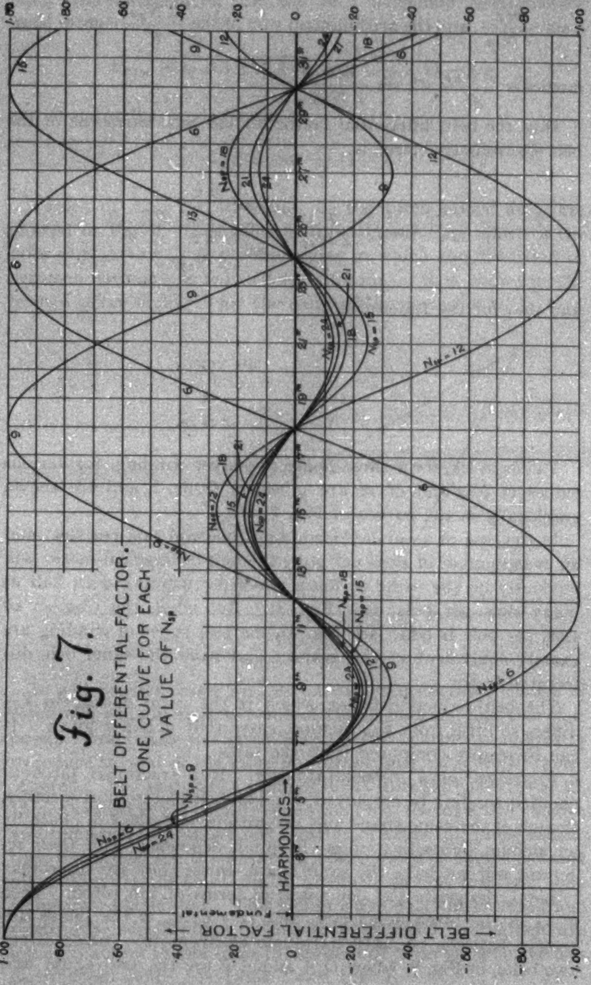

Fig. 7.

BELT DIFFERENTIAL FACTOR.
ONE CURVE FOR EACH
VALUE OF N_{sp}

$2 \sin \frac{m\pi}{2N_{sp}}$, and the arithmetical sum of the $\frac{2N_{sp}}{p'}$ mth harmonics is $\frac{2N_{sp}}{p'} \times 2 \sin \frac{m\pi}{2N_{sp}}$.

Thus the belt differential factor for the mth harmonic of the belt electromotive force is:

$$k_{dm} = \frac{p'}{2N_{sp}} \frac{\sin \frac{m\pi}{p'}}{\sin \frac{m\pi}{2N_{sp}}}$$

and that for the fundamental

$$k_{d_1} = \frac{p'}{2N_{sp}} \frac{\sin \frac{\pi}{p'}}{\sin \frac{\pi}{2N_{sp}}}.$$

Values of k_{dm} for a three-phase two-layer winding, for various values of N_{sp} and of m, are given in Table I, and are shown graphically in the curves of Fig. 7.

In the case of a one-layer winding (one coil-side per slot) and an even number of slots per pole, the belt differential-factor will obviously be the same as for a two-layer winding with half as many slots per pole, (see Fig. 3). But when the number of slots per pole is odd, (see Fig. 4), the two types of winding are exactly equivalent in this respect and have the same belt differential-factor.

The belt reduction-factor which is the ratio of k_{dm} to k_{d_1}, differs so little from k_{dm} in most cases that it is not given. It can be readily computed from the table.

Fractional pitch differential-factor. If a fractional pitch or chorded winding be employed, the two belt electromotive forces, though of the same shape and magnitude, will differ in phase by an amount depending upon the pitch deficiency, and their resultant will not have the same shape unless they are sinusoidal.

Let λ_c designate the coil pitch in terms of full pitch. Then $1 - \lambda_c$ is the pitch deficiency, and $(1 - \lambda_c)\,\pi_m$ is the phase difference between the mth harmonic electromotive forces of the two belts, in Fig. 8, where $\overline{OA}$ and $\overline{AB}$ are the two equal mth harmonic electromotive forces and $\overline{OB}$ their resultant. The pitch differential-factor for the mth harmonic electromotive force is then:

$$k_{pdm} = \overline{OB} \div 2\,\overline{OA} = \cos\frac{m\pi}{2}(1-\lambda_c)$$

and that for the fundamental is,

$$k_{pd_1} = \cos\frac{\pi}{2}(1-\lambda_c)$$

Values of k_{pdm} for all values of the pitch above 50% are plotted in Fig. 9. *The pitch reduction factor* k_{pm}, which is the ratio of k_{pdm} to k_{pd_1} shows the degree in which the distortion or per cent harmonic is reduced by chording. It is shown in the broken curve of Fig. 9 for the eleventh harmonic only.

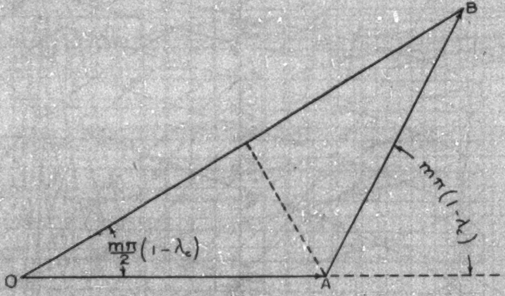

FIG. 8

It will be seen from Fig. 9 that any considerable change of pitch will usually reverse some of the harmonics, and that it is possible practically to eliminate any desired harmonic, or greatly to reduce several of the more important ones, by a proper choice of pitch. For example, a pitch of 0.833 (five slots in 6, 10 in 12, 15 in 18 or 20 in 24) would reduce the fifth, seventh, seventeenth and nineteenth to about one quarter of their full pitch values; then by connecting the phases in star, (which is equivalent to a pitch of 0.667), the third, ninth, fifteenth, twenty-first, etc., may be entirely eliminated. This would leave only the eleventh and thirteenth, which would ordinarily be reduced by the belt differential action to less than 10 per cent of their value in the flux distribution curve, see Table I and Fig. 7.

Mid-coil differential factor. If the phase winding begin and end in the center of a coil rather than at the junction of two coils, there will be two half-coil vectors, as shown in Fig. 5, where $\overline{o' d'}$ is

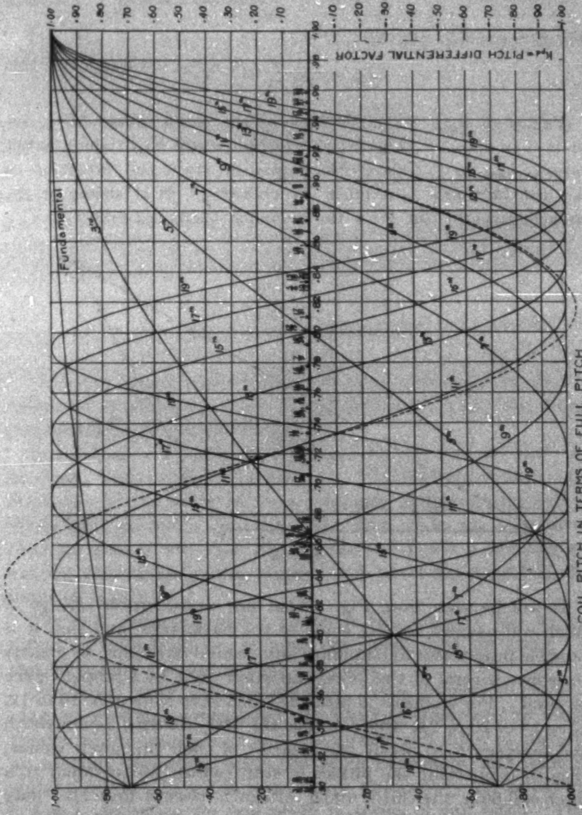

FIG. 9

drawn from the middle of No. 1 electromotive force to the middle of No. 5 electromotive force, and in Fig. 6 where $\overline{o_3' d_3'}$ is drawn from the middle of 1_3 to that of 5_3. The resultant is thus reduced in the ratio.

$$k_{dcm} = \cos \frac{m\,\pi}{2\,N_{sp}}$$

which is the *mid-coil differential factor* for the *m*th harmonic.

For the fundamental this is

$$k_{dc_1} = \cos \frac{\pi}{2\,N_{sp}}\ .$$

and the *mid-coil reduction factor* for the *m*th harmonic is

$$k_{cm} = \frac{k_{dcm}}{k_{dc_1}} = \cos \frac{m\,\pi}{2\,N_{sp}} \div \cos \frac{\pi}{2\,N_{sp}}$$

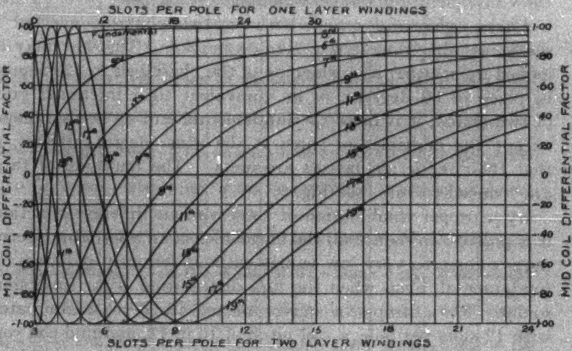

FIG. 10

Since k_{cm} is so nearly equal to k_{dcm}, the latter only is given in the curves of Fig. 10. The values given in Fig. 10 apply strictly only to the two-layer winding, but it has already been shown that in the case of an even number of slots per pole, the one-layer winding is equivalent to a two-layer winding with half as many slots per pole, and that in the case of an odd number of slots per pole, the one-layer winding is wholly equivalent to the two-layer winding.

With ordinary values of N_{sp} some of the higher harmonics are practically eliminated, and others are considerably reduced by the mid-coil connection.

Summary

There are thus several differential actions combining to reduce the electromotive force induced in the armature of an alternator, but they affect the fundamental and the various harmonics in different degrees, the amount of reduction of the fundamental being in general very small as compared with that of the harmonics. These differential actions may be classified as follows:

Belt differential action, between the several slots of each phase belt;

Pitch differential action, between the two belts of each coil group;

Mid-coil differential action, due to the mid-coil connection and the consequent equivalent widening of each belt;

Phase differential action, between two phases connected in series, as with three-phase star connection. This last may be looked upon either as a widening of the phase belt to 120 degrees in place of 60 degrees, or as equivalent to a fractional pitch of two-thirds; it reduces the fundamental and all the harmonics except the multiples of three in the same degree, (0.866), so that their reduction factors are unity. The multiples of three are reduced to zero, see Fig. 9.

By a proper combination of these various differential actions it is possible to reduce all the harmonics of an alternator electromotive force to very low values without seriously reducing the fundamental, even when the flux distribution is far from sinusoidal. For example, a star-connected three-phase alternator, with 12 slots per pole, a coil pitch of 10 in 12, and mid-coil connections, will have per cent harmonics in its electromotive force wave which bear to the per cent harmonics of the flux distribution curve the following ratios, labelled k_r, the *total reduction factor*.

$m =$	3	5	7	9	11	13	15	17	19	21
$k_r =$	0.0	0.045	0.023	0.	0.017	0.017	0.0	0.027	0.045	0.0

In this case the least reduction is to less than 5 per cent of the per cent value in the flux distribution curve, and if the largest harmonics in the flux distribution curve were not more than 10 per cent, the largest harmonics in the electromotive force wave would be less than one half of one per cent. But by a proper

TABLE II
TOTAL REDUCTION FACTOR FULL-COIL CONNECTION

		3rd	5th	7th	9th	11th	13th	15th	17th	19th
$N_{sp} = 6$	$\lambda_c = \frac{6}{6}$	+0.732	+0.268	-0.268	-0.732	-1.000	-1.000	-0.732	-0.268	+0.268
	$\lambda_c = \frac{5}{6}$	+0.536	+0.072	+0.072	+0.536	+1.000	+1.000	+0.536	+0.072	+0.072
	$\lambda_c = \frac{4}{6}$	0.000	-0.268	+0.268	0.000	-1.000	-1.000	0.000	+0.268	-0.268
$N_{sp} = 9$	$\lambda_c = \frac{9}{9}$	+0.695	+0.227	-0.185	-0 347	-0.185	+0.227	+0.695	+1.000	+1.000
	$\lambda_c = \frac{8}{9}$	+0.611	+0.148	-0.064	0.000	+0.064	-0.148	-0.611	-1.000	-1.000
	$\lambda_c = \frac{7}{9}$	+0.370	-0.042	+0.151	+0.415	+0.151	-0.042	+0.370	+1.000	+1.000
	$\lambda_c = \frac{6}{9}$	0.000	-0.227	+0.185	0.000	-0.185	+0.227	0.000	-1.000	-1.000
$N_{sp} = 12$	$\lambda_c = \frac{12}{12}$	+0.682	+0.214	-0.165	-0.283	-0.132	+0.132	+0.283	+0.165	-0.214
	$\lambda_c = \frac{11}{12}$	+0.636	+0.172	-0.101	-0.109	-0.017	-0.017	-0.109	-0.101	+0.172
	$\lambda_c = \frac{10}{12}$	+0.499	+0.058	+0.044	+0.207	+0.132	-0.132	-0.207	-0.044	-0.058
	$\lambda_c = \frac{9}{12}$	+0.283	-0.089	+0.165	+0.283	+0.055	+0.055	+0.283	+0.165	-0.089
	$\lambda_c = \frac{8}{12}$	0.000	-0.214	+0.165	0.000	-0.132	+0.132	0.000	-0.165	+0.214
$N_{sp} = 15$	$\lambda_c = \frac{15}{15}$	+0.677	+0.209	-0.156	-0.258	-0.114	+0.107	+0.209	+0.107	-0.114
	$\lambda_c = \frac{14}{15}$	+0.647	+0.182	-0.117	-0.153	-0.047	+0.022	0.000	-0.022	+0.047
	$\lambda_c = \frac{13}{15}$	+0.560	+0.107	-0.017	+0.082	+0.078	-0.998	-0.214	-0.998	+0.078
	$\lambda_c = \frac{12}{15}$	+0.418	0.000	+0.097	+0.258	+0.114	-0.066	0.000	+0.066	-0.114
	$\lambda_c = \frac{11}{15}$	+0.229	-0.114	+0.167	+0.229	+0.013	+0.078	+0.229	+0.078	+0.013
	$\lambda_c = \frac{10}{15}$	0.000	-0.209	+0.156	0.000	-0.114	+0.107	0.000	-0.107	+0.114
$N_{sp} = 18$	$\lambda_c = \frac{18}{18}$	+0.674	+0.206	-0.152	-0.247	-0.106	+0.096	+0.181	+0.088	-0.088
	$\lambda_c = \frac{17}{18}$	+0.653	+0.188	-0 125	-0.175	-0.061	+0.041	+0.047	+0.008	+0.008
	$\lambda_c = \frac{16}{18}$	+0.592	+0.135	-0.053	+0.000	+0.037	-0.063	-0.159	-0.088	+0.088
	$\lambda_c = \frac{15}{18}$	+0.493	+0.055	+0 041	+0.181	+0.106	-0.096	-0.132	-0.240	-0.240
	$\lambda_c = \frac{14}{18}$	+0.358	-0.038	+0 124	+0.294	+0.087	-0.018	+0.096	+0.088	-0.088
	$\lambda_c = \frac{13}{18}$	+0.192	-0.131	+0 167	+0.192	-0.010	+0.087	+0.052	+0.041	+0.041
	$\lambda_c = \frac{12}{18}$	0.000	-0.206	+0.152	0.000	-0.106	+0.096	0.000	-0.088	+0.088

TABLE III
TOTAL REDUCTION FACTOR MID-COIL CONNECTION

		3rd	5th	7th	9th	11th	13th	15th	17th	19th
$N_{sp} = 6$	$\lambda_c = \frac{6}{6}$	+0.536	+0.071	+0.071	+0.536	+1.000	+1.000	+0.536	+0.071	+0.071
	$\lambda_c = \frac{5}{6}$	+0.392	+0.020	-0.020	-0.392	-1.000	-1.000	-0.392	-0.020	+0.020
	$\lambda_c = \frac{4}{6}$	0.000	-0.071	-0.071	0.000	+1.000	+1.000	0.000	-0.071	-0.071
$N_{sp} = 9$	$\lambda_c = \frac{9}{9}$	+0.611	+0.148	-0.064	0.000	+0.064	-0.148	-0.611	-1.000	-1 000
	$\lambda_c = \frac{8}{9}$	+0.536	+0.096	-0.022	0.000	-0.022	+0.096	+0.536	+1.000	+1.000
	$\lambda_c = \frac{7}{9}$	+0.325	-0.027	+0.052	0.000	-0.052	+0.027	-0.325	-1.000	-1.000
	$\lambda_c = \frac{6}{9}$	0.000	-0.148	+0.064	0.000	+0.064	-0.148	0.000	+1.000	+1.000
$N_{sp} = 12$	$\lambda_c = \frac{12}{12}$	+0.636	+0.172	-0.101	-0.109	-0.017	-0.017	-0.109	-0.101	+0.172
	$\lambda_c = \frac{11}{12}$	+0.592	+0.137	-0.063	-0.042	-0.002	+0.002	+0.042	+0.063	-0.138
	$\lambda_c = \frac{10}{12}$	+0.263	+0.072	+0.101	+0.109	+0.007	+0.007	+0.109	+0.101	+0.072
	$\lambda_c = \frac{9}{12}$	+0.465	-0.046	+0.027	+0.080	+0.017	-0.017	-0.080	-0.027	+0.046
	$\lambda_c = \frac{8}{12}$	0.000	-0.172	+0.101	0.000	-0.017	-0.017	0.000	+0.101	-0.172
$N_{sp} = 15$	$\lambda_c = \frac{15}{15}$	+0.646	+0.182	-0.117	-0.153	-0.047	+0.022	0.000	-0.022	+0.047
	$\lambda_c = \frac{14}{15}$	+0.618	+0.159	-0.087	-0.090	-0.019	+0.005	0.000	+0.005	-0.019
	$\lambda_c = \frac{13}{15}$	+0.535	+0.093	-0.012	+0.048	+0.032	-0.021	0.000	+0.021	-0.032
	$\lambda_c = \frac{12}{15}$	+0.400	0.000	+0.072	+0.153	+0.047	-0.014	0.000	-0.014	+0.047
	$\lambda_c = \frac{11}{15}$	+0.219	-0.099	+0.125	+0.136	+0.005	+0.016	0.000	-0.016	-0.005
	$\lambda_c = \frac{10}{15}$	0.000	-0.181	+0.116	0.000	-0.047	+0.022	0.000	+0.022	-0.047
$N_{sp} = 18$	$\lambda_c = \frac{18}{18}$	+0.653	+0.188	-0.125	-0.175	-0.061	+0.040	+0.047	+0.008	+0.008
	$\lambda_c = \frac{17}{18}$	+0.634	+0.171	-0.102	-0.124	-0.035	+0.017	+0.012	+0.000	-0.000
	$\lambda_c = \frac{16}{18}$	+0.574	+0.122	-0.043	+0.000	+0.021	-0.027	-0.041	-0.008	-0.008
	$\lambda_c = \frac{15}{18}$	+0.478	+0.050	+0.033	+0.128	+0.061	-0.041	-0.034	-0.002	+0.002
	$\lambda_c = \frac{14}{18}$	+0.348	-0.034	+0.101	+0.209	+0.049	-0.007	+0.025	+0.008	+0.008
	$\lambda_c = \frac{13}{18}$	+0.187	-0.118	+0.138	+0.137	-0.006	+0.037	+0.013	+0.004	-0.004
	$\lambda_c = \frac{12}{18}$	0.000	-0.188	+0.124	0.000	-0.061	+0.041	0.000	-0.008	-0.008

choice of pole arc it is easy to reduce the fifth harmonic of the flux distribution curve to 5 per cent and since the nineteenth would never be as large as this, the maximum harmonic in the electromotive force wave would in this case be about two tenths of one per cent of the fundamental.

Tables II and III contain values of the *total reduction factor* k_r for a considerable range of values of N_{sp}, m and λ_c. The tables as they stand apply directly to the two-layer winding only, but it will be remembered that a one-layer winding with an odd number of slots per pole per phase is entirely equivalent to a two-layer winding with the same number of slots, and that a one-layer winding with an even number of slots per pole per phase is equivalent (for the present purpose) to a two-layer winding with half as many slots.

EXAMPLES

The curves of Mr. Bache-Wiig's Atlantic City paper provided such an excellent illustration of the value of the method above outlined that they are reproduced in Figs. 11, 12, 13 and 14.

Curve I of Fig. 11 is an assumed flux distribution curve or "field form" of a two-pole, three-phase, 60-cycle, 400-kw. turbo-alternator with 12 slots per pole. The other 16 curves were computed from the "field form" by the ordinary method for the various windings indicated on the curves.

The eight curves of Figs. 12 and 14 giving the phase voltage, and the flux distribution curve of Fig. 11, have been analyzed for the purposes of this paper. The results are given with the corresponding calculated values in Table IV.

In making comparisons it should be remembered that there were many opportunities for errors in the original computing, plotting, reproducing, transcribing, and analyzing. The method of analysis employed is that of Fischer Hinnen* and while it is very simple, it suffers from the fact that the correction made necessary in any lower harmonic by the presence of a multiple of that harmonic, is of the full magnitude of that multiple. This requires for reasonably accurate results that the analysis be carried to the higher multiples; but the probable error in the determination of these higher multiples is so great that it renders the lower harmonics less accurate than would otherwise be possible. The slice or strip† method in which areas are used instead of ordinates, is more accurate in this respect when carefully carried out, but the amount of labor involved for accurate results was too great for the task in hand.

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* "Electrotechnische Zeitschrift", May 9, 1901; also "Electric Journal", 1908.

† Houston and Kennelly in "Electrical World", 1898.

After carrying the analysis of all the curves to the nineteenth harmonic, it was surmised that the correction due to still higher harmonics might have a considerable effect. This was found to be true by carrying the analysis of the flux distribution curve to the twenty-seventh harmonic, but time was not available for carrying the analysis of the other curves to the same point, so that some of the minor discrepancies are doubtless due to this omission.

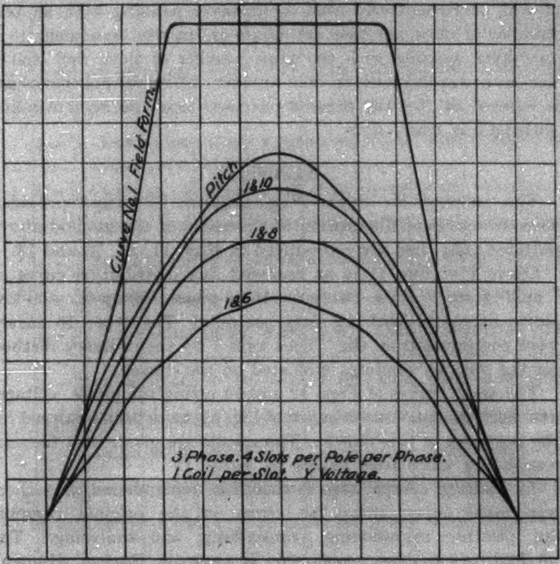

FIG. 11

Referring now to Table IV:

Under "*flux distribution curve*" are given the results of the analysis of that curve, (Fig. 11), the harmonics being given in per cent of the fundamental.

TABLE IV

ANALYSIS AND CALCULATIONS OF BACHE-WIIG'S CURVES

			Pitch curve $\lambda_c = 1$		"1 & 10" curve $\lambda_c = \frac{9}{12} = .75$			"1 & 8" curve $\lambda_c = \frac{7}{12} = .583$			"1 & 6" curve $\lambda_c = \frac{5}{12} = .417$		
	Harmonics	Flux dist. curve	Analyzed from *B-W* pitch curve	Calc. from flux dist.	Anal. from *B-W* "1 & 10" curve	Calc. from pitch curve	Calc. from flux dist.	Anal. from *B-W* "1 & 8" curve	Calc. from pitch curve	Calc. from flux dist.	Anal. from *B-W* "1 & 6" curve	Calc. from pitch curve	Calc. from flux dist.
One-layer winding. One coil-side per slot. Fig. 12	Fundamental	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	3rd Harm.	+2.46	+1.78	+1.80	+0.86	+0.73	+0.74	0.10	−0.86	−0.87	−2.80	−2.70	−2.73
	5th "	−8.80	−1.91	−2.36	+0.94	+0.79	+0.97	+3.66	+2.39	+2.95	+0.43	+0.41	+0.50
	7th "	−1.32	+0.5	+0.35	−0.44	−0.50	−0.35	+1.11	−0.08	−0.06	+0.48	+0.81	+0.57
	9th "	+2.46	−0.6	−1.80	+1.75	+0.60	+1.80	−0.84	−0.70	−2.09	+0.9	+0.38	+1.13
	11th "	+0.09	+0.04	−0.09	+0.04	−0.02	+0.04	+0.78	+0.03	−0.07	0.0	−0.05	+0.12
	13th "	−1.42	+0.06	+1.42	+0.46	+0.02	+0.58	−0.02	−0.04	−1.09	+1.26	+0.08	+1.85
	15th "	−0.03	0.0	+0.02	0.00	0.00	+0.02	+0.02	0.0	−0.02	0.0	0.0	+0.01
	17th "	+0.81	+0.06	−0.22	0.0	+0.06	−0.22	0.0	+0.01	−0.03	−0.11	−0.10	+0.36
	19th "	−0.02	−0.05	0.0	+0.05	−0.02	−0.00	0.0	−0.06	−0.00	0.0	−0.01	0.0
Two-layer winding. Two coil-sides per slot. Fig. 14.	Fundamental	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	3 d Harm.	+2.46	+1.44	+1.66	+0.96	+0.59	+0.68	−0.41	−0.69	−0.80	−2.47	−2.18	−2.51
	5th "	−8.80	−1.88	−1.89	+0.29	+0.78	+0.78	+1.88	+2.35	+2.36	—	+0.40	+0.41
	7th "	−1.32	+0.22	+0.22	−0.35	−0.22	−0.22	+0.17	−0.04	−0.04	+0.54	+0.36	+0.36
	9th "	+2.46	−0.36	−0.69	+0.62	+0.36	+0.69	—	−0.42	−0.80	+1.07	+0.23	+0.44
	11th "	+0.09	−0.23	−0.01	−0.35	+0.09	—	—	−0.18	−0.01	—	+0.30	+0.01
	13th "	−1.42	−0.12	−0.20	−0.15	−0.05	−0.08	+0.12	+0.09	+0.15	−0.14	−0.16	−0.26
	15th "	−0.03	−0.12	−0.01	−0.2	−0.12	−0.01	−0.16	+0.14	+0.01	−0.24	−0.08	−0.01
	17th "	+0.81	−0.06	+0.13	−0.2	−0.06	+0.13	—	−0.01	+0.02	—	+0.10	−0.21
	19 "	−0.02	−0.04	0.00	—	−0.02	—	—	−0.05	—	—	−0.01	—

Under "*pitch curve*" are compared the analyzed harmonics of the full pitch curve with those obtained by calculation from the harmonics of the flux distribution curve by means of Table I.

Under "1 *and* 10 *curve*" are compared the analyzed harmonics of the "1 and 10" curve with those obtained by calculation from both the pitch curve and the flux distribution curve.

The same explanation applies to the other fractional pitch curves.

Referring to the two columns under "pitch curve" in Table IV there are only two out of the eighteen comparisons where the computed harmonic differs by more than a reasonable error from that obtained by direct analysis.

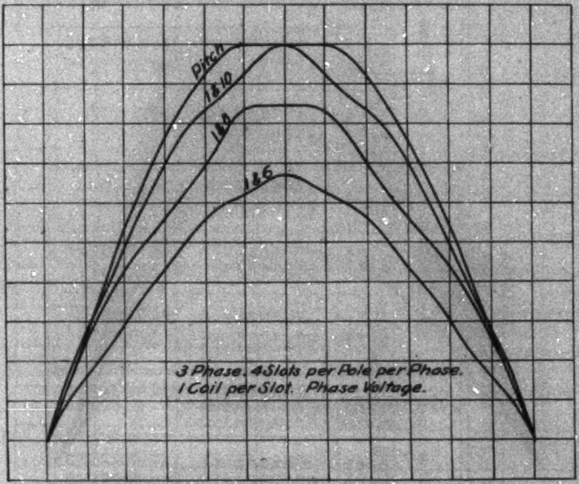

FIG. 12

Referring to the remainder of the table relating to the fractional pitch curves, the results calculated from the flux distribution curve are on the average closer to those obtained by direct analysis than those computed from the pitch curve, showing that some of the above-mentioned discrepancies under "Pitch Curve" were in the pitch curve itself or in its analysis, rather than in the flux distribution curve or in its analysis. This is reasonable since the flux curve harmonics, being larger, are determinable with a smaller percentage error.

The only considerable discrepancies in the fractional pitch results are those for the "1 and 8" curve and the one-layer winding, and it is altogether likely that there was some slip in the original computation or plotting of this curve, since the results for the same pitch in the two-layer winding, computed from the same flux harmonics, are much closer.

Referring again to Fig. 12 it is interesting to note the reversal of the harmonics in passing from one pitch to another as indicated by the curves of Fig. 9.

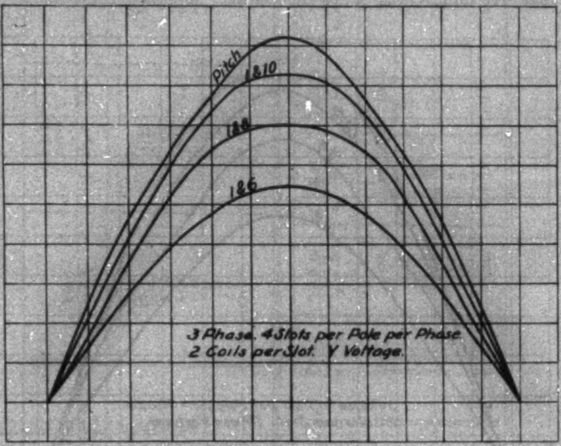

FIG. 13

Thus all the results shown in the curves of Figs. 11, 12, 13, and 14 can be obtained in a much more useful form and with greater accuracy than by the ordinary method and with the expenditure of a small fraction of the time.

As another example, Fig. 15 shows an observed flux distribution curve for a two-pole, 300-kw. turbo-alternator.

Table V gives the harmonic analysis of this curve together with the harmonics of the phase electromotive forces for all possible pitches down to 50 per cent (assuming $N_{s\phi} = 12$), from which it appears that with star connection to wipe out the third, ninth, and fifteenth harmonics, no one of these windings would give an electromotive force with any single harmonic larger than one per cent of the fundamental. This is not at all an extreme case since the pole arc is normal, being about 65 per cent of the pole pitch.

By employing the two-layer winding, star connection, and a pitch of ten slots or 83.3 per cent, the harmonics would assume the following values, in per cent of the fundamental, the largest being less than two tenths of one per cent, and the others less than five hundredths of one per cent.

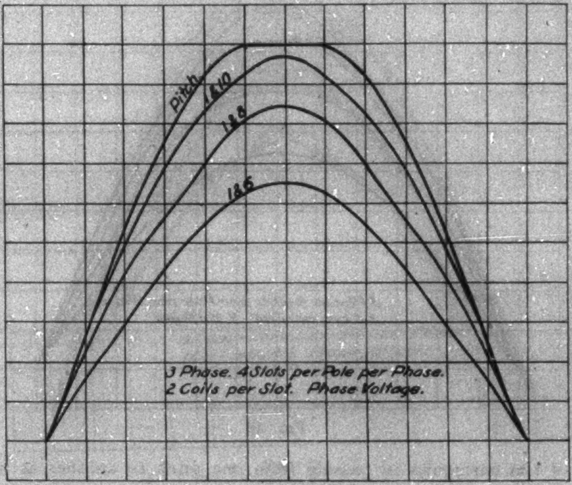

FIG. 14

m =	1	3	5	7	9	11	13	15	17	19
% =	100.0	0.0	0.043	0.003	0.0	0.15	0.0	0.0	0.0	0.002

Conclusion. It is fully realized that there are several considerations beside that of wave-shape which affect the choice of winding type in an alternator, but there are certainly some

TABLE V

	Harmonics	Flux distribution curve	Pitch curve $\lambda_c = 1$	"1 & 10" curve $\lambda_c = \frac{9}{12} = 0.75$	"1 & 8" curve $\lambda_c = \frac{7}{12} = 0.583$	"1 & 6" curve $\lambda_c = \frac{5}{12} = 0.417$
One-layer winding. One coil side per slot.	Fundamental	100%	100%	100%	100%	100%
	3rd Harm.	20.6	15.1	6.21	-7.27	-22.8
	5th "	2.83	0.76	-0.31	-0.95	-0.16
	7th "	-0.30	0.08	-0.08	-0.013	0.13
	9th "	-1.90	1.39	-1.39	+1.62	0.87
	11th "	-0.80	.80	-0.33	+0.61	1.04
	13th "	0	0	0	0	0
	15th "	0	0	0	0	0
	17th "	0	0	0	0	0
	19th "	-0.12	-0.032	-0.013	-0.04	+0.007

	Harmonics	Flux distribution curve	Pitch curve $\lambda_c = 1$	"1 & 12" curve $\lambda_c = .916$	"1 & 11" curve $\lambda_c = 0.833$	"1 & 10" curve $\lambda_c = 0.75$	"1 & 9" curve $\lambda_c = 0.667$	"1 & 8" curve $\lambda_c = 0.583$	"1 & 7" curve $\lambda_c = 0.50$
Two-layer winding. Two coil sides per slot.	Fundamental	100%	100%	100%	100%	100%	100%	100%	100%
	3rd Harm.	20.6	14.05	13.1	10.5	5.79	0	-6.77	-14.05
	5th "	2.83	0.61	0.49	0.16	-0.25	-0.61	-0.76	-0.61
	7th "	-0.30	0.05	0.03	-0.013	-0.05	-0.05	-0.01	+0.05
	9th "	-1.90	0.54	0.21	-0.39	-0.54	0	+0.62	+0.54
	11th "	-0.80	0.152	0.02	-0.15	-0.06	+0.15	+0.12	-0.15
	13th "	0	0	0	0	0	0	0	0
	15th "	0	0	0	0	0	0	0	0
	17th "	0	0	0	0	0	0	0	0
	19th "	-0.12	0.026	-0.022	+0.007	+0.01	-0.026	+0.012	-0.026

instances where an accurate knowledge of the relation of winding type to wave-shape would materially influence the choice of the former much to the advantage of the latter. Also, even when certain harmonics are practically absent from the flux distribution curve at no load, they may be present under full-load distortion, so that the choice of a winding with low reduction factors (see Tables II and III) is in general desirable, other things being equal.

Finally the knowledge as to which harmonics can be practically eliminated by a possible choice of winding makes it possible to choose the pole arc, or shape the pole face, so as to eliminate the principal remaining harmonics. A good example of this is given above, and illustrated in Fig. 15.

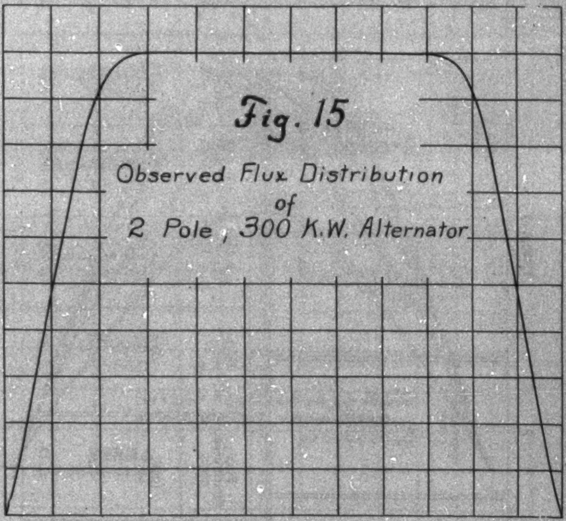

Fig. 15

Observed Flux Distribution of 2 Pole, 300 K.W. Alternator

The writer wishes to take this opportunity of thanking Mr. Bache-Wiig for the use of the curves of Figures 11, 12, 13, 14 and 15, and Mr. Julian Tynz for his careful analysis of these curves.

DISCUSSION ON "ELECTROMOTIVE FORCE WAVE-SHAPE IN ALTERNATORS." FRONTENAC, N. Y., JUNE 30, 1909

J. C. Lincoln: I would ask Professor Adams if he has any particular pitch winding to recommend in order to give the best results in eliminating these higher harmonics?

C. A. Adams: The curves of Fig. 9 show the reduction of the various harmonics for all pitches above 50 per cent. The pitch that reduces the larger harmonics most effectively is a pitch of 10 slots in 12; it reduces the 5th, 7th, 17th, and 19th harmonics to about one-quarter of their value in the full-pitch winding. The 3rd, 9th, and 15th can be entirely cut out by star connection. This leaves only the 11th and 13th harmonics with their full pitch magnitudes, and these are usually small.

J. C. Lincoln: A pitch of about 84 per cent then?

C. A. Adams: Yes; approximately.

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THE MODERN TELEPHONE CABLE

BY FRANK B. JEWETT

To those not closely in touch with the telephone situation to-day, the importance of the modern telephone cable may be indicated by stating that of the 8,000,000 miles of wire in the exchange plants of the associated Bell telephone companies, more than 6,800,000 miles are in the form of underground, aerial, or submarine cable. These figures refer solely to the wire used for outside construction and do not include the thousands of miles of wire in cable form employed in central offices or in the wiring of large buildings.

At the present time the bulk of the cable in any telephone plant is used in connection with exchange construction in urban districts. For a large part of such work the concentration of hundreds of circuits in the form of cables is the only available method of providing the facilities necessary to meet present-day service demands, which in many of the larger cities exceed one telephone for each 20 inhabitants, and in a few cities more than one for each 10 inhabitants.

It should be clearly recognized, however, that even the best cable circuit is much less efficient than an open-wire circuit; for example, one mile of the No. 19 B. & S. gauge cable circuit ordinarily employed in exchange construction results in as much current attenuation as 35 miles of No. 8 B. W. G. open-wire copper toll circuit, or 3.5 miles of the smallest size open-wire iron circuit used in rural exchange work. From these figures it is apparent that the extensive use of cable necessarily results in a material reduction of the radius within which satisfactory commercial transmission can be given, and as the most advanced telephone art to-day is only with difficulty meeting the increasing demands for long-distance service, cables can be substituted for open wires only when the further maintenance of open-wire circuits becomes impracticable. It is on account of this decrease in efficiency that the telephone company expends such large sums to retain open-wire circuits for its toll lines as close as possible to the central office, but even in this portion of the plant increasing numbers of circuits have forced the abandonment of pole lines in certain situations.

In another direction also the necessity for cable construction has developed to a certain extent; namely, providing the necessary circuit facilities between very large cities separated by moderate distances and between which there is a great deal of terminating telephone business; thus at the present time the business between New York and Philadelphia, New York and New Haven, and Chicago and Milwaukee, is handled over all-cable circuits.

The extensive application of cable construction in the modern telephone plant just outlined has been made possible only through the development of a form of cable exceedingly efficient as compared with the earlier forms. It is the purpose of this paper to consider a few of the essential requirements which have had to be met in the production of such a cable. While certain features of the manufacturing processes are described in order to explain the method of obtaining certain characteristics, the paper is in no sense an exposition of the technique of cable manufacture. In order to show how the telephone engineer ensures the production of a cable having the desired characteristics, clauses covering the points discussed have been taken from the standard form of cable specifications employed by the associated Bell companies.

THE ESSENTIAL REQUIREMENTS OF THE MODERN TELEPHONE CABLE

The essential requirements for an efficient and satisfactory telephone cable, while primarily electrical, are of course unavoidably connected with mechanical and cost restrictions. These requirements, which must be fulfilled by the cable and which form the basis of present-day cable specifications, are briefly as follows:

1. That the cable shall provide the maximum number of independent and non-interfering circuits within the minimum space.

2. That these circuits shall have the maximum transmission efficiency for currents of telephonic frequency, compatible with the other electrical and mechanical requirements.

3. That the dielectric strength of the cable shall be such as to insure against failure from any of the potentials normally employed and to make possible its protection against damage from lightning and from foreign circuits operating at potentials in excess of those employed on telephone lines.

4. That the mechanical arrangement adopted to obtain the necessary electrical properties shall be such as to insure a continued maintenance of these properties after the cable has been installed. This assumes a construction which will withstand the hard usage unavoidably connected with cable installation.

5. That this mechanical construction shall be made at a cost which will render the cable circuits economically available in comparison with other known means of circuit provision.

In addition to the foregoing, certain subsidiary requirements dealing with the general size of the cable desired; that is, the size of wire and number of pairs required; the method of circuit identification (color scheme); the length of cable sections to be furnished; the method of preparation for shipment and some form of guarantee which will insure high-grade material and workmanship in the manufacture of the cable, are ordinarily covered in the cable specification.

Standard cable construction. While differing somewhat in details, the essential features of all modern telephone cables, known as dry-core paper-insulated, are the same whether the wires are in the little five-pair or ten-pair subscribers' cables ordinarily strung on pole lines or in the largest sizes employed underground. Cables of this type are in one respect fundamentally different from cables which employ rubber or gutta-percha insulation. In the latter construction the dielectric which surrounds the wire serves not only to keep the wires in proper position, but being itself impervious to moisture, the dielectric serves to maintain the efficiency of the circuit, whether exposed to moisture or not. The telephone cable, on the other hand, belongs to that class of cable in which any solid dielectric employed is used primarily as a mechanical separator or to give the requisite dielectric strength. In this class of cable the deleterious effects of moisture are guarded against by surrounding the conductors with a water-tight metallic sheath.

For making up telephone cables, wires of the proper size are first insulated by wrapping them individually with dry paper ribbon. This ribbon, which is usually about $\frac{5}{8}$ in. wide and of a thickness varying from 0.002 in. upward, depending on the size of the wire, and colored in some distinctive fashion, is spirally applied, but not with such a tension as to cause it to adhere closely to the wire. For the ordinary underground or aerial cable a single wrapping of paper suffices; in some forms of submarine cable two wrappings of paper, laid on in reversed directions, are used. In any event, the ribbon is so well overlapped that the wire is completely covered. Thus insulated, the wires are twisted together in pairs, the two wires of a pair being insulated with different colored papers and the length of twist depending upon the size of the conductors and the use to which the cable is to be put. The maximum length of twist, however, rarely exceeds 6 in. and for the smaller size of wires is ordinarily under 4 in. This twisting of the individual circuits is for the purpose of neutralizing inductive and capacity effects, which would occasion "crosstalk" between the various circuits if the wires of the core were laid up parallel to one another.

The core of the cables is made up in cylindrical form by assembling the requisite number of twisted pairs in concentric layers one or more pairs thick, the pairs in each layer being arranged spirally about the axis of the core and the direction of rotation in the alternate layers being reversed. As explained below, this use of a concentric layer construction is adopted to insure the necessary mechanical stability for the completed cable. The number of pairs in each layer is dependent upon the size and capacity of the cable required and is varied by changing the size of the central strand.

When the cylindrical core has been completed, it is wrapped with one or more thicknesses of paper tape to bind the conductors firmly in place, present a smooth exterior surface, and prevent the lead of the sheath from coming in contact with the insulation of the outer layer of conductors. This wrapping also gives the higher dielectric strength needed in the pairs of the outer layer. During the process up to this point the paper, being hygroscopic, has unavoidably taken on more or less moisture which must be removed before the sheath is applied. To this end the core, suitably reeled, is placed in a drying oven in which air at a high temperature is circulated for a considerable period, after which the core is taken immediately to the lead press and the final sheath is applied. This completes the process except for the testing, sealing of the ends and reeling for shipment.

While the individual wires forming the core of the cable just described are wrapped with paper, the cable is essentially different from the ordinary paper-insulated power cable, in that it is in effect an air-core construction. The paper, which is loosely applied and fills only a part of the total space not occupied by the conductors, is deformed in the process of cabling and serves merely as a mechanical separator to keep the wires apart and not as a dielectric *per se*, or as the carrier for a dielectric compound. In cable of this type the real dielectric is the dry air between the wires.

To show how nearly the present dry-core cable meets the essential requirements of the telephone industry, it may be interesting to examine some of these requirements and their actual fulfilment in detail and also the evolutionary process by which the present form of construction has been arrived at.

Choice of the dielectric.

Specification requirement: Each conductor shall be insulated with a single wrap of paper spirally applied.

In designing a cable for high-frequency current transmission work the principal requirement, as previously noted, is that it shall combine the maximum number of independent non-interfering circuits having a maximum of transmission efficiency within the minimum space and at a minimum cost. It is essential, therefore, that the dielectric selected for maintaining the proper separation of the wires and providing the necessary mechanical properties required of the cable should have both a low dielectric capacity and small dielectric hysteresis. These features, which in power cables designed for transmitting large amounts of low-frequency, high-potential current may be of secondary importance compared with high insulation and high dielectric strength, become paramount when the question is one of securing an efficient cable for the transmission of small currents having frequencies ranging up into the thousands of periods per second, and in which high dielectric strength is a matter of secondary consideration. The importance of these characteristics of the dielectric is readily apparent when we come to examine the mathematical expressions for the propagation of high-frequency currents such as those met with in telephony.

For a uniform metallic circuit containing resistance, inductance, capacity and leakage uniformly distributed, the formula for the attenuation constant is

$$a = \sqrt{\tfrac{1}{2}\sqrt{(R^2+L^2\omega^2)\ (S^2+C^2\omega^2)} + \tfrac{1}{2}(RS - LC\omega^2)}$$

In this formula R, L, and C have the ordinary significance, being respectively the resistance, inductance, and shunt capacity expressed in ohms, henrys and farads, while ω has the ordinary significance, being 2π times the frequency, and S, which represents the shunt leakage in parallel with the shunt capacity, expressed in mhos, is a measure of the combined direct-current conductance as determined from the insulation of the cable and also of the apparent conductance which results from the energy loss due to dielectric hysteresis.

For telephone cables where the wires are close together the inductance is negligibly small and the formula reduces to

$$a = \sqrt{\frac{R}{2}\left(\sqrt{S^2 + C^2\omega^2} + S\right)}$$

or when the leakage component is small in comparison with the capacity component, to approximately

$$a = \sqrt{\frac{RC\omega}{2}}\left(1 + \frac{S}{2C\omega}\right)$$

This is the formula which ordinarily applies to cable circuits employed for telephonic transmission, and it will be noted that where S is zero; that is, for cables having high insulation and no dielectric dissipation, the expression for the attenuation constant is merely that of the so-called "KR law." The quantity $\frac{S}{2C}$ in the above formula, known as the "damping constant," is dependent on the dielectric of the cable and is independent of the capacity of the cable, provided the dielectric is unchanged in character by changing the separation of the wires. In order, therefore, that the transmission efficiency of any cable shall be high for some particular frequency or range of frequencies, it is necessary that in addition to low capacity, the dielectric shall have the smallest possible ratio of shunt conductance to shunt capacity for these frequencies.

In the following table are given the constants at one thousand periods per second for No. 19 B. & S. gauge cables made up with rubber insulation, braided-cotton insulation impregnated with paraffin, and dry-core paper insulation. In each case the cables have the constants normal to the particular kind of construction. From this table it will be noted that for rubber-insulated and cotton-impregnated-insulated cables both the capacity and conductance are materially higher than in the dry-core, paper-insulated cable.

CONSTANTS OF No. 19 B. & S. GAUGE TELEPHONE CABLES

Insulation	Mutual capacity mf. per mile 1000 p.p.s.	Mutual conductance m. mhos per mile 1000 p.p.s.	Damping constant $S/2C$ 1000 p.p.s.
Rubber	0.15	40	133
Braided cotton filled with paraffin	0.12	16	67
Dry-core paper	0.08	2	12.5

Taking the constants of the foregoing table and applying them in the approximate formula, it will be seen that the attenuation constant of the impregnated cable is 24 per cent, and that of the rubber 40 per cent higher than that of the dry-core paper cable; also that while the dissipation of the dielectric increases the attenuation in the latter cable by less than 0.2 per cent at 1000 periods per second, that in the impregnated cable increases it by 1.05 per cent and in the rubber insulated cable by 2.10 per cent. In addition to the effect of dielectric dissipation increasing the attenuation of the cable, the fact that this increase is not constant for all frequencies but it is greater the higher the frequency, results in a cable with high dielectric dissipation having more distortion than one in which the dissipation is low over the range of frequencies involved in speech transmission.

From the above table it is also evident from the small value of the dissipation constant for the dry-core cable that with this type of construction conditions have been attained approximating very close to those in which nothing but air would intervene between the wires. In addition to the numerous mechanical, electrical, and economic defects which obtained in impregnated and rubber-cored cables, the fact that they were materially inferior in efficiency to the present type of dry-core construction was one of the principal factors leading to the adoption of the latter.

While the standard telephone cable of to-day is essentially an air-core cable, the amount of solid dielectric necessary for mechanical reasons is appreciable, and in specifying a wrapping of high-grade dry-rope paper ribbon the aim has been to utilize a material which will have the lowest possible dielectric capacity and dissipation, and at the same time possess the necessary mechanical properties to permit of its use in comparatively small quantities. That the paper should be spirally applied to the wires rather than put on in some other fashion, is the result of actual experience with other types of construction. In the early days of dry-rope paper insulation, numerous schemes for applying the paper were suggested and tried, with the result that spiral application was found to afford the greatest immunity from accidental crosses during installation while at the same time requiring a minimum amount of solid material in the core.

Insulation resistance.

Specification requirement: In every length of cable each conductor shall show an insulation resistance of not less than 500 megohms per mile of cable at 68 degrees fahr., each conductor being measured against all the rest and the sheath.

For telephone cables made in the United States the foregoing requirement is the one ordinarily specified. In Europe the insulation requirements are frequently very much more severe than this, and sometimes necessitate drying the cable after it is laid and spliced.

It is extremely doubtful, however, whether a high insulation specification can be justified in view of the extra expense incident to meeting it and the exceedingly small improvement in transmission resulting therefrom. The results of American practice have indicated that the specification of an insulation resistance which will insure honest manufacturing processes, a reasonable amount of drying and a permanent product, is all that is warranted. As a matter of fact the regular drying processes adopted ordinarily give an insulation resistance materially above 500 megohms, although under the exceptionally humid conditions frequently prevailing in the summer months, the insulation at times approaches the specification figure.

An inspection of the foregoing attenuation formula and the constants for different dielectrics will show at once that high insulation is not in itself necessarily an indication that the cable will be efficient. Thus rubber-insulated cables which have an insulation resistance of thousands of megohms per mile are decidedly less efficient than dry-core cables of the same capacity whose insulation is 500 megohms per mile. Since the principal dielectric loss in a dry-core cable results from dielectric hysteresis, rather than from direct conduction the specification of an insulation resistance requirement must, as previously stated, be looked upon primarily as one to insure an efficient process of manufacture and provide for a cable core which will not be subject to deterioration. The effect of this drying on the insulation and dielectric constant of the cable is shown in the following table of measurements made on a cable core before and after immersion in the regular drying tank. It will be seen that while the insulation has been improved materially by the removal of moisture the great improvement so far as efficiency is concerned has come from the reduction of the dielectric capacity and dielectric hysteresis in the cable.

Effect of Drying Paper Cable
300 pair No. 19 B. & S. Gauge.

Insulation megohms per mile		Mutual capacity mf. per mile		Damping constant $S/2C$ (1000 p.p.s.)	
Green core	Finished cable	Green core	Finished cable	Green core	Finished cable
300	1550	0.082	0.071	19	12

Thus while the transmission efficiency has been increased 7.1 per cent by the process of drying, the improvement due directly to the increased insulation resistance is less than 0.001 per cent, that due to the reduced capacity being 7.0 per cent and that to the reduced damping constant 0.1 per cent. As to whether further drying would not result in still further improvement it can be said that beyond the period of drying ordinarily employed, the dielectric capacity and damping constant of paper show but little further reduction even with the most elaborate drying by chemical processes. Such processes, on account of their expense, could probably never be justified in any but exceptional cases.

Dielectric strength.

Specification requirement. The insulation of each conductor shall be capable of withstanding a potential of 500 volts without rupture.

All dry-core paper-insulated cables used by the associated Bell telephone companies are required to withstand a direct-current potential of 500 volts between any wire and its mate, or between any wire and all the remaining wires and the sheath of the cable. As noted previously, this requirement is incorporated not only to guard against the danger from failure due to the normal potentials met with in telephone operation, but chiefly that the cable circuits may be efficiently protected from lightning or when they come in contact with light or power circuits. Past experience has shown that efficient protection without unduly great maintenance charges can be obtained only by providing open space cut-outs which will operate at potentials lower than the break-down potential of the cable. As it is not feasible to maintain open space cut-outs with operating potentials much below 500 volts, this figure marks the minimum dielectric strength which admits of suitable protectors. For certain classes of cable, where the exposure conditions either to power circuits or to lightning are exceptionally severe, or where, as at submarine cables crossing in the center of long toll lines, the inability quickly to clear trouble or repair damage would involve serious interruptions of service, special high dielectric requirements are frequently specified.

Electrostatic capacity.

> Specification requirements: In every length of cable the average mutual electrostatic capacity of all the pairs and the mutual electrostatic capacity of any pair per mile of cable at a temperature of 68 degrees fahr. shall not exceed the values given in the following table, the capacity shall be measured between one wire of a pair and its mate, the remainder of the conductors being connected to the sheath.

For cables used in exchange construction, such for instance as No. 19 gauge of 300 pairs or less, the mutual capacity referred to in the above quotation ordinarily averages slightly below 0.080 mf. Thus for a 300 pair No. 19 B. & S. gauge cable the specification average is 0.077 mf. and the maximum 0.084 mf. per mile for each length, while for cables of 240 pairs or less the corresponding figures are 0.070 mf. and 0.079 mf. respectively.

In the foregoing specification requirement the capacity is that measured by the ordinary charge or discharge method. While this constant is not that directly applicable to the computation of transmission efficiency for high frequencies, it is justified in manufacturing specifications on account of the difficulty of making accurate high-frequency determinations. It is also justified by the fact that in a thoroughly dried cable the capacity determined by the discharge method is not greatly in excess of the high-frequency capacity. This is indicated by the following table which gives the capacities of a small condenser having a cable paper dielectric 0.0085 in. thick, before and after the latter had been subjected to the ordinary drying process. It will be noted that in the undried state the difference between the discharge and high-frequency capacities is large. In a properly drawn specification the capacity requirement is a check on the insulation requirement as a guarantee of proper drying, it being impossible to provide the requisite number of pairs having the proper capacity in the specified sheath with an insufficiently dried core and still maintain the requisite dielectric strength.

EFFECT OF DRYING CABLE INSULATING PAPER.

Condition of paper	Thickness of paper	Capacity of condenser micro-microfarads		
		Discharge	1000 p.p.s.	2000 p.p.s.
Undried........	0.0085 in.	11000	7020	6953
Dried..........	"	5793	5780	5779

With dry-core paper construction by a proper cabling of the pairs, the capacity of the cables can be varied at will within a moderate range to meet different transmission conditions, while at the same time retaining the necessary mechanical and electrical properties. Owing to irregularities in manufacture and differences in location within the core, not all the pairs have exactly the same capacity. For this reason, it is customary to specify both an average mutual capacity limit for all the pairs in each length and also the maximum mutual capacity limit of any one pair. This insures the proper efficiency for the completed cable run without putting such a stringent limitation on the uniformity of the product as to render the cost excessive.

It is now customary to specify mutual rather than grounded capacity, as the former is a constant of the cable directly indicative of its transmission efficiency. So far, however, as insuring efficient construction and good workmanship is concerned, either mutual or grounded capacity would suffice, since within the range of capacities ordinarily met with in telephone cables the relation between the mutual capacity of a pair and the grounded capacity of its component wires is fairly constant, the mutual capacity being approximately 60 per cent of the grounded capacity.

If an attempt is made to secure too low a capacity by separating the wires and employing too small an amount of paper, the core becomes so soft that the completed cable is easily deformed, and consequently extremely hard to handle; on the other hand, any attempt to secure an extremely high capacity by putting an excessive number of pairs in the core renders the cable stiff and unwieldy, or if the amount of paper is sacrificed the dielectric strength will be unduly low. Experience has shown that an average mutual capacity of about 0.050 mf. per mile marks the lower limit for single-wrap paper cable which can be readily handled without undue deformation, while approximately 0.09 mf. per mile marks the upper limit. Between these two limits practically any desired capacity can be obtained, although on account of having to conform to a limited number of cabling schemes it is not always possible to secure a uniform gradation of capacity with a specified sheath diameter and number of pairs.

Sheath.

Specification Requirement: The core shall be enclosed in a sheath composed of an alloy of lead and tin, the amount of tin by weight to be not less than 3 per cent. The sheath shall be free from holes or other defects and shall be of uniform composition and thickness. The thickness and outside diameter shall be for any size of cable as called for in the table given below.

For the mechanical protection of the core wires during and after installation and for preventing the ingress of moisture at all times, a continuous sheath composed of an alloy of lead and tin is moulded firmly about the finished and dried core. This sheath, which varies in thickness from $\frac{1}{12}$ in. to $\frac{1}{8}$ in. for aerial and underground cables, depending upon the size of the core, is molded in a continuous section over each individual length of core immediately on the removal of the latter from the drying oven.

To insure uniformity of practice in the cable plant it is necessary to set some limit on the maximum diameter of the sheath. At the present time the standard for a full size cable is $2\frac{5}{8}$ in. outside diameter, this being the limiting size that can be satisfactorily drawn into a standard 3 in. duct. A cable of this size will contain 300 pairs of No. 19 B. & S. conductors having the capacity noted above.

No single problem connected with the development of the modern telephone cable has probably been so difficult of solution as deciding upon the proper type of sheath, and the brief specification clause quoted above embodies the results of years of experience. Unlike most of the other features of the cable, the proper requirements for the sheath could not be forecast to a large extent and many indeed have resulted from conditions developed since the use of cable was first begun.

At the time when impregnated-cotton-insulated cable was the standard construction, the sheath was formed up separately and the core drawn in. This necessitated a considerable amount of clearance between the sheath and the core and although the entire inner space was ultimately filled with paraffin or resin oil, the cable had a decided tendency to buckle and crack if bent on any except a long radius. For this reason and because it was frequently necessary to relocate cables in the plant, early specifications usually contained a clause stating that the completed cable must be capable of being wound and unwound a certain number of times on a drum of specified diameter without buckling or cracking. This requirement was to insure that the cable would be serviceable when withdrawn from the duct.

The process also limited the length of sheath which could be continuous, so that where long pieces of large cable were needed to fit suitable manhole spacings, factory joints in the sheath had to be resorted to. The care in making these so as to withstand the rough treatment incident to pulling into the duct was such as to greatly increase the difficulties and expense of manufacture. As a result of the defects in the earlier forms the present process was developed of moulding the sheath directly on to the dried core so as to closely fit it, eliminating at once the necessity for factory joints and the need for clearance between the core and sheath.

The specification of a 3-per cent tin alloy for the sheath is likewise a result of experience gained in the early days of cable development. Added primarily for the purpose of hardening the sheath so as to better withstand rough usage during manufacture and installation, the amount of tin used was long a matter of individual preference. The present standard requirement was only arrived at when a careful investigation was made to determine the proper remedy for the cracking of aerial cable sheaths, which developed when the sheath was subjected to continued vibration. At the time there was a very strong sentiment in favor of a pure lead sheath for such cables, a sentiment based largely on the poor showing made by alloy sheaths in a number of instances and the feeling that a softer sheath would be less likely to crystallize. It was only when exhaustive laboratory experiments had shown the great superiority of a proper alloy over pure lead that the final solution was reached.

The following table gives some results of a series of experiments on the ability of different materials to withstand rupture when subjected to continued vibration under stress. In each case the test samples were strips 4 in. long, narrowed for 2 in. in the center to a section measuring $\frac{1}{2}$ in. by $\frac{3}{64}$ in. One end was fastened to a metal tongue pressing lightly against a toothed wheel and the noted weight suspended from the lower end. The tongue was given approximately 108 complete vibrations per second. Where two weights are noted the larger was added to hasten rupture.

VIBRATION STRAIN FOR CABLE SHEATH MATERIALS

Material	Weight suspended	Time of stress
1. Lead Pure...............	13 lb. 2 oz.	55 m.
2. " "	6 lb.	10 hr. 15 min.
3. Lead 99.5%, tin 0.5%....	13 lb. 2 oz.	32 hr.
4. Lead 99.0%, tin 1.0%....	*a*—13 lb. 2 oz. *b*—23 lb. 2 oz.	74 hr. with "*a*" and 1 hr. " "*b*"
5. Lead 97.0%, tin 3.0%....	*a*—13 lb. 2 oz. *b*—23 lb. 2 oz.	48 hr. with "*a*" and 9 hr. " "*b*"

With the advent of creosoted wooden conduit a great deal of trouble from the chemical corrosion of the sheaths was experienced. In these earlier ducts, wood creosote was the preservative agent employed but owing to the presence of considerable acetic acid, this had a ruinous action on sheath materials. Elaborate experiments at the time proved that while not wholly free from such corrosion, the 3-per cent tin alloy sheath was corroded much less than one of pure lead or one with but a small proportion of tin. While improvements in the process of creosoting by the substitution of dead oil of coal tar for wood creosote, thereby eliminating the acetic acid, and the advent of vitrified clay ducts, have practically eliminated chemical corrosion from the field of cable trouble, it was one of the factors which at the time led to the adoption of the present standard sheath material. Although an excess of tin renders the alloy too hard and brittle, only the minimum limit needs to be specified, the high price of tin automatically keeping the amount used as small as possible.

Cable specifications. In conclusion, a word might be said about the standard cable specifications to which reference has already been made. These specifications aim primarily to secure a certain standard for the finished product without unduly restricting the manufacturer as to the exact processes he shall employ to attain the desired end. While certain of the mechanical characteristics are incorporated, such as the use of a particular alloy for the sheath, and the employment of paper insulation to the exclusion of other materials, it is on account of experience having shown them to be the best available.

As a result of this aim, the specifications, though brief, have the clauses so drawn as to insure the equivalent of a process known to be satisfactory. In the matter of brevity the present-day specification is analogous to the earliest specifications, which also aimed at a suitable finished product without specifying particular processes. There is this marked difference however: much of the brevity of the earlier specifications was due to an insufficient knowledge of the characteristics and possibilities of the materials and processes employed, while the brevity today is the result of a definite knowledge gained from long experience and a more comprehensive conception of the fundamental laws governing the efficient transmission of high-frequency currents, of just what each material will do under varying conditions and just what the limitations of any particular process are.

Between the specifications of the late '80's and those of to-day a period intervened in which it was frequently customary to specify minutely the exact process to be employed and the behavior of the finished cable under widely differing conditions, such, for instance, as the specification of just what the allowable capacity should be at a number of different temperatures. And however much future specification requirements may differ from those of today as regards subject matter, owing to advances in the art, the laws governing the propagation of currents along wires are sufficiently well known to make a recurrence of this type of specification unlikely.

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THE TRAINING OF NON-TECHNICAL MEN

BY C. R. DOOLEY

In electrical engineering the proper and efficient arrangement of iron, copper, and insulation, is only a part of the problem. The proper and efficient arrangement of brain and muscle, providing for higher individual efficiency of all classes of men who are to carry on the business of the future, is the fundamental part of the engineering problem and therefore should merit the most careful consideration of an engineering society such as the Institute.

This part of the problem should not be left entirely to the engineering colleges, for they are unable to arrive at a complete solution. In the first place the engineering schools supply a very small number, perhaps less than one per cent, of the men required to carry on the business. In the second place their graduates are practically all led along one line to a single level. There are few if any college courses in salesmanship, foremanship, shop management, etc. Few colleges expect their graduates to become skilled mechanics, tool designers, or even draftsmen. The manufacturer of electrical apparatus needs a few highly trained men to carry on scientific research, but he just as greatly needs laborers, skilled mechanics, efficient clerks, shop directors, inspectors of materials and hundreds of artisans, and all these need training to develop the best that is in each man for the direct benefit of his employer.

The need of special and general training for all classes of men instead of for one class, is strikingly emphasized by the great number of commercial enterprises that are providing for their men systematic training in a combined scientific and practical way.

The educational activities in the vicinity of the Westinghouse interests at East Pittsburg divide themselves into two general classes: 1. The training of the graduates of engineering schools. 2. The training of non-technical men. It is the purpose of this paper to describe the work that is being carried on along the latter line.

The training of non-technical men is further divided into two distinct lines: 1. The apprenticeship system, which includes a certain amount of systematic class instruction given during working hours. 2. The night school, where attendance is purely voluntary. Both of these have a place in the training of non-technical men.

The situation. The present scarcity of skilled workmen is a matter of great moment to the manufacturer. He is vitally concerned in plans for the future that will insure men of all-around skill in their respective lines. He may rely upon the engineering schools for the majority of his managers, but who will broaden and train his workmen? The present highly specialized labor is proving inadequate in many shops for two reasons: 1. The dwarfing of the ambitions of the men. 2. The almost total absence of old-time all-round mechanics, which restricts the transfer of workmen from one section of a shop to another.

This is the age of specialization, but the extreme specialization that is seen on every hand will kill the best impulses of human nature and ruin our national endeavor. Almost every machine shop in the country is filled with special machinists, or rather machine specialists; in short, machine-men. Man is not a machine. To allow him to become a mechanical producer instead of a thinking producer, is not only wrong ethically, but is rapidly being recognized as wrong economically.

That which is best for the individual is best for the concern for which he works. The managers of large concerns are eagerly looking forward to the increase in the productive power of the workmen, and will willingly pay for it accordingly. The question of the future is not how to get a man to do a day's work for the least pay, but how to get the most efficient work out of the man, increasing his pay in proportion.

The apprenticeship system. The development of the boy and not "shop production" should be the watchword of the apprenticeship department of every company. At the works of the electric company already referred to, the apprenticeship department is being developed in a most systematic and careful manner, the first vice-president of the company taking an active part. In this establishment the work of the apprentices is divided into two departments: 1. The shop. 2. The classroom.

In the shop the plan is to devote a certain section to the apprentices. This section is fitted with a complete equipment to furnish shop-practice in all branches of the machinists' trade. In the shop the boys are under the guidance of shop instructors having the rank of foremen. These instructors are all-around mechanics taken from the shop organization and chosen for their interest in young men as well as for their skill as workman. The boys are moved from machine to machine, from operation to operation, in systematic order and are at all times under the guidance of the shop instructors. The boys remain in this section approximately two years. The latter half of their course is spent in the various sections of the shop. During this period they do not have the direct attention of the shop instructors but are under the care of the apprenticeship department and are transferred about the works as is deemed best for the individual boy, according to his natural ability.

In the classroom the instruction is provided on the company's time, and is conducted throughout the four years of the course. This work is a part of the daily schedule, and the apprentices report to the classroom as systematically as to their shop foremen. Special rooms inside the works have been fitted with suitable tables, desks, blackboards, etc., much the same as any ordinary schoolroom. However, the atmosphere is hardly that of a schoolroom, but rather that of a class where the boys are given problems and explanations concerning the things with which they work every day, instead of problems in abstract mathematics. In connection with the character of the class work there are three vital points: 1. The scientific principles underlying the subjects must be taught. 2. These scientific principles can best be presented through the working out of practical problems dealing with the things of the boy's everyday life. This will hold his interest. 3. The same problem must teach him certain facts and specific knowledge concerning the things with which he is working, such as weights, costs, and strength of materials, gear speeds, pulley and belt speeds, etc. In fact, a knowledge of the things with which the problems deal and the facility offered for thinking about these very ordinary things, may be the most valuable features of this instruction.

As a specific case consider the subject of addition of frac-tions and mixed numbers. Instead of an abstract group of such quantities to be added, the boy is given this problem:

> A shaft has two shoulders. The length from one end to the nearest shoulder is 3⅞ in. The length between shoulders is 1 ft. 4½ in. The length from the second shoulder to the other end is 4¾ in. Allowing $\frac{3}{16}$ in. at each end for finish, what length of stock will be required to make four shafts?

Nor is this type of problem too simple for the average apprentice. Out of a class of 103 beginners, 45 could scarcely add or multiply decimal quantities and knew practically nothing about proportion and percentage.

There is yet another phase of the work without which all else will fail. For want of a better name we call it spirit. It includes loyalty and enthusiasm, not only in the work and the future it holds for the boys, but also in all their daily relations with their fellows—a spirit of service and willingness, confidence in all things and all people, and eternal optimism. This may be illustrated by the following incident: The second week of the operation of the class work included a holiday which happened to come on Monday. One boy in the Monday class complained of his hard luck in losing a period owing to the holiday. Another boy was congratulating himself upon being in the Tuesday class.

At present the class work is scheduled under two general heads: 1. Mechanical drawing. 2. Shop arithmetic. Each of these subjects embraces a certain amount of the general subjects of shop problems, tool construction, tool operation, shop organization, and system, as well as the fundamental science of the subject itself.

The night school. The best organized apprenticeship system, even with its supplemental classroom work, will not satisfy the more ambitious young men. Such men are studying every spare moment; they are taking correspondence courses or are attending night school. They are not satisfied with learning a trade, but have a desire for a broader training leading toward engineering. There is a prevalent feeling that engineering training applies only to college men, that for the 95 per cent of the boys of the country who never finish high school, the problem is one of industrial education with specific training in definite trades. While this is perhaps true in the majority of cases, it is not a foregone conclusion.

A night school is not necessarily a trade school. On the contrary, a night school may do high-grade engineering work, in fact, from some points of view a properly organized night school, or some other form of close coöperation between technical training and commercial practice, may offer the best opportunity for engineering training. One thing that makes for high efficiency in night-school work is the character of the men who pursue it. The schedule of work is necessarily difficult, and hence only the more industrious and ambitious boys will take it up. The very nature of this system is selective in the beginning, but the selection is natural and self-appointed and therefore just. Another thing is the daily contact with the intensely commercial sides of all problems, the theoretical sides of which are explained in the schoolroom. If during four years of the study of theoretical and experimental electricity in the night school, the student is employed during the daytime in a power house, on a wire gang, winding and insulating armatures or assembling switchboards, he will get a type of engineering training that is in great demand.

Six years ago The Casino Technical Night School was started in the vicinity of the manufacturing works already referred to. Its management is independent of any commercial industry, though its activity is encouraged and fostered by the local organizations, including the public school board, the latter furnishing the housing. In the beginning there were half a dozen teachers and a few dozen students who attended classes in drawing, elementary mathematics, and shop practice. There is now offered an opportunity for systematic study in such fundamentals as mathematics, mechanical drawing, mechanics, physics, theoretical and applied electricity, chemistry, shop practice in both wood and iron, theoretical and applied steam engineering, etc. There is a faculty of 25 instructors and an enrolment of about 300 students. The growth and development has been along sure and conservative lines and only as rapid as the demands of the students required, and yet in the 6 years the actual number of hours that each student devotes to the entire course has been increased over seven-fold; from two sessions of 40 min. each, on two evenings for a term of 2 years, to three sessions of 60 min. each, on three evenings each week for a term of 4 years.

The instructors are themselves not only versed in the theory of their respective subjects but each is also actively engaged during the day with his subject within the organization of a commercial factory. The advantages in the way of securing exceptionally trained teachers are therefore ideal.

Attendance is voluntary and a small tuition fee is charged. Admission is extended to all, regardless of occupation or previous education. The low educational entrance qualifications are cared for by a preparatory department. Practically all the students are employed in the various shops in this vicinity for the regulation 9.75 hr. per day besides attending school 3 hr. on three evenings each week. The schedule of work is such that they cannot possibly keep up without devoting several of the remaining evenings of the week to the preparation of their lessons. Though the school has a vacation period from June to September, these men are devoting practically all of their time to study and to work—to the acquisition of scientific knowledge and commercial experience. In addition to this it is a common thing for groups of students to request additional work. During the past year a class of some 15 students met once a week after school—after 9:15 p.m.—to study English. These men not only did this work in addition to their regular schedule but bore the extra expense necessary to maintain the class.

Perhaps it will be thought, this is too much. But is it any more than the aggressive man in commercial activity is doing and expects to do the balance of his life? Is it not exactly what the 25 instructors are doing? These instructors have their daily routine in shop, testing room, drafting room, and engineering department. The pay for their school work is small, but the work is both interesting and broadening. The relation between students and instructors is ideal—they learn and teach with an absolute mutual confidence and personal interest.

This wholesome spirit finds expression in many ways, notably in the conduct of the classroom where matters of discipline are practically unknown; in class organization, the presidents of the several classes organizing themselves into a student council for the furthering of the interests of the school; and in the general interest shown at commencement time when the year's work is drawn to a close with appropriate exercises comprising orations by members of the graduating class and an address by a prominent engineer or educator, and a dinner which marks the very climax of enthusiasm and loyalty.

Nor has the social side of student life been omitted. The boys have organized a glee club, a mandolin club, a basket-ball team, and a base-ball team. They also edit and publish a small monthly bulletin. These clubs are well organized and would do credit to many a college organization.

The total enrolment just before the financial depression was something over 300. For the year just closed it was approximately 250. In general, 80 per cent of those who enroll complete the term's work. Of the 45 men who have been graduated during the past three years, practically all have been steadily advanced in position and responsibility, and 40 are still with their original employers. While no degree can be given the graduates, the character of their work and the positions held by the men after graduation may warrant the assertion that the Casino school is, if not the first night school, among the first to graduate men in engineering. Some of the graduates are doing high-grade engineering work in the engineering department and in the drafting office of the nearby electrical manufacturing company. Others are successful salesmen and many are doing responsible work in the erection department and in the shop organization.

The engineering night school has a large field of activity. At the start its students possess a clear idea of commercial practice which the newly graduated college student seldom has. This early experience instills an appreciation of the value of time and of the value of scientific training that tends to produce the most efficient student. They have learned several years earlier in life that scientific study and commercial practice not only go hand in hand but that they should continue hand in hand throughout life if the highest achievements are to be attained; that there never comes a time when the one can be laid aside and the other taken up. They also know the importance of the routine of life, that from the office boy to the president, it is the fellow who gets the job done who gets the bigger job to do.

While it is not within the province of a manufacturing concern to provide a liberal education for its men, with the present degree of general education among young boys it is within the principles of good business to provide and maintain a training in those fundamental subjects which will assist in developing skilled mechanics and workmen of higher ideals to carry on the business of the future. Further, a manufacturing concern can well afford to assist and encourage the exceptional young man to as high a technical training as he will take.

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THE VALUE OF THE CLASSICS IN ENGINEERING EDUCATION

BY CHARLES P. STEINMETZ

Education is not the learning of a trade or profession, but is the development of the intellect and the broadening of the mind, afforded by a general knowledge of all the subjects of interest to the human race, as required to enable a man to attack intelligently and solve problems in which no previous detail experience guides, and to decide the questions arising in his intellectual, social, and industrial life by impartially weighing the different factors and judging their relative importance. These problems, and thus the educational preparation required to cope with them, are practically the same in all walks of life, and the general education of mind and intellect required by the engineer, the lawyer, the physician, etc., thus is essentially the same. The only legitimate differences in the training for the life's work, required by the different professions, thus are those pertaining to the specific instruction and study of the details of the particular branch of human knowledge by which the student desires to make his living.

For ages the classics, comprising the study of the Latin and Greek languages and the literature of these languages, have been the foundation of all education; but in the last two generations they have been more and more pushed into the background by the development of empirical science and its application, engineering. It is my opinion that this neglect of the classics is one of the most serious mistakes of modern education, and that the study of the classics is very important and valuable, and more so in the education of the engineer than in most other professions, for the reason that the vocation of an engineer is specially liable to make the man one sided. By dealing exclusively with empirical science and its applications, the engineer is led to forget, or never to realize, that there are other branches of human thought besides empirical science, and equally important as factors of a broad general education and intellectual development. An introduction to these other fields is best and quickest given by the study of the classics, which opens to the student other worlds entirely different from our present, the world of art and literature, of Hellas, and the world of organization and administration—and of citizenship—of Rome, and so broadens his horizon beyond anything which can be accomplished otherwise, and shows relative values more in their proper proportion, and not distorted by the trend of thought of his time.

It is true that the classics are not necessary if the aim is to fit the student to ply the trade of engineer, just as that of plumber or boiler maker, and the world, and especially the United States, is full of such men who have learned the trade of engineer. But such learning of the engineering trade can hardly be called receiving an education, and certainly does not fit the man to perform intelligently his duties as a citizen of the republic during the stormy times of industrial and social reorganization, which are before us.

There also is a considerable utilitarian value in the classic languages, as the terminology of science is entirely based on Latin forms with Greek and Latin roots, and while the student may memorize the terms of his profession, it is difficult, if not impracticable, to memorize all the terms of science with which an educated man must be familiar as those of medicine, botany, mineralogy, etc. This however becomes easy to the student of the classic languages, to whom these terms have a meaning. To eliminate the scientific terms of objects from the language is obviously impossible, as the common or English names usually are different in different localities, if they exist at all, and thereby indefinite.

The modern languages are not in the same class with the classic languages, as they open to the student no new world, no field of thought appreciably different from our own, and I therefore consider them of practically no educational value. Their utilitarian value to the college student is negligible, as due to the limited time, the absence of practice, and the large number of other more important subjects of study, very few of the college graduates retain even a rudiment of their knowledge of modern languages, and even those few only because they are especially interested in them, have occasion to practice them, and therefore would probably have learned them outside of college. To the engineer particularly, the knowledge of foreign modern languages offers no appreciable help in following the engineering progress of other countries, as practically all that is worth reading is translated into English either in full or in abstract, and engineering publications written in a foreign language are closed to the reader even if he has some knowledge of the language, by his lack of knowledge of the technical terminology of the foreign language.

Since the modern languages have no appreciable educational value, they should be dropped from the engineering curriculum of the college, as their retention violates the principle of the modern college curriculum, to restrict, owing to the limited available time, the instruction to those subjects which the student can not acquire outside of the college by self-study, or can acquire only under great difficulties. Modern languages do not belong to this class, but are learned just as easily, if not more easily, by self-study and conversation.

Referring to the classics, however, it is true that the methods of their teaching are not the most efficient, and especially the classic literature with which the student is familiarized, is not selected so as to offer the greatest educational value in broadening the student's view, nor so as to attract and retain his interest as much as possible, but rather seems to be the result of survival from previous times.

Thus in Latin the story of war and conquest, of the victory of military organization over mere bravery, in *Caesaris de bello Gallico*, is interesting and instructive, while the Civil war is of less interest. Even to-day *Ciceronis de officiis* is well worth reading, while *Ad Catilinam* is stupefying to the intellect, since any intelligent boy must ask why did the "man afraid of his shadow" not have Catilina arrested and executed for high treason.

In Latin poetry selections from *Ovidii Metamorphoses* are very easy reading, and are a valuable introduction to the classic metre, and interesting in the parallelism of the myths of the classic world with those of other races (the flood etc.), but it is hard to understand the retention of the uninteresting plagiarism of the courtier Virgil in the curriculum, while the most important, in his educational value, and most interesting poet, Horace, is not read at all in most college curricula. Of all Roman writers, Horace probably exerts the most broadening influence on the intellect when read under an intelligent instructor; the change from the distortion in which the relative values of persons and things appear to their contemporaries, to the proper proportion in the perspective of history, probably is nowhere so sharply demonstrated as in the relation between the "*libertino patre natus*" and his "protector" and "patron," Maecenas, whose name has escaped oblivion merely by his favorite's favor, while Horace promises immortality to whatever he addresses, and confers it (*ad fontem Bandusiam*). The reading of Horace probably is the best remedy for discouragement resulting from lack of appreciation of one's efforts, as the engineer and the inventor very often has reason to feel. Also especially the American, who is generally liable to take himself too seriously, might benefit from the sentiment expressed in *Ad Leuconoen*. In short almost every one of Horace's poems is interesting and instructive and conveys a moral which we may well listen to.

In Greek prose, *Xenophontis Anabasis* is interesting and instructive in many respects, and may well be followed by the student with maps of the country traversed by the ten thousand. Selections from Lucian possibly are the nearest approach to Horace in their broadening influence. The Greek drama probably is beyond the scope of reading which can be attempted in a general college course, and also appears to me less important now, where in the modern northern drama we have similar tendencies exhibited. The easy dialect of the κοινη however is within the reach of the student, and at least a part of the new testament may be read in the original and its value can hardly be overestimated in showing the meaningless nature of theological controversies on words of an imperfect translation. The greatest work of the literature of Hellas however is Homer; and here again in many American schools the *Iliad* only is read, possibly from the mistaken notion that it is easier reading, while the far more interesting *Odysee* is slighted, though the latter with its tales of travel and adventure, with giants and monsters, should especially appeal to the American boy, and is of far greater interest and educational value in its minute description of everyday life at the early dawn of human history, in its pictorial expressions of times and occupations, of the time of the day, the coming of night, the dawn, etc. Nowhere possibly is found such a vivid description of omnipotence as in Homer's:

Ἦ καὶ κυανέῃσιν ἐπ᾽ ὀφρύσι νεῦσε Κρονίων·
Ἀμβρόσιαι δ᾽ ἄρα χαῖται ἐπερρώσαντο ἄνακτος
Κρατὸς ἀπ᾽ ἀθανάτοιο, μέγαν δ᾽ ἐλέλιξεν Ὄλυμπον.

DISCUSSION ON "THE TRAINING OF NON-TECHNICAL MEN" AND "THE VALUE OF CLASSICS IN ENGINEERING EDUCATION." FRONTENAC, N. Y., JULY 1, 1909.

C. P. Steinmetz: In the preceding paper I desired to make a strong plea for the reestablishment of the classics as one of the most important and valuable educational factors necessary to give that intellectual development and broadening of the mind which produces not merely intellectual machines, but citizens of the Republic capable of taking their proper place in the industrial and social life of the nation. From the standpoint of educational value I consider the classics superior to any modern language. I do not mean to say that modern languages should not be learned; very much the contrary; what I believe is that modern languages have no place in a college curriculum. They should be studied privately or as an elective study, and preferably in early youth. Furthermore, I also do not mean to imply that our present method of teaching the classics is particularly perfect. Indeed, the major part of the paper is a criticism of our present method of classical study.

I might say a few words on the origin of the paper. I have noticed for many years that in the higher positions connected with the electrical engineering industry the number of men who have risen without any college education is far out of proportion to what could possibly be the case if in the broad development of the mind the college were all that it should be.

Furthermore, during recent years we engineers have been impressed forcibly with the circumstance that we do not occupy in the public life of the nation the position that we should occupy, and must expect to occupy, owing to the importance of our profession. We have complained that bodies appointed to deal with the relations of the states and the nation to engineering in its industrial and social aspect do not contain a single engineer. When considering the situation, thinking what I would do if I had to appoint such commissions, I was forced to conclude that I also would act in the same manner: I might appoint a man who is an engineer in spite of his being an engineer, but not because he is an engineer. This is an unfortunate situation. The cause of it was brought to my mind more fully by reading the paper presented by Mr. F. P. Fish last May,* not because of the contents of the paper, but because of its style and atmosphere, which are such that no mere engineer could have written it, but a classical scholar.

This is a matter which must be changed. We engineers must insist on occupying in the public life of the nation that position which is due to us as exponents of the most important branch of human thought and work. But before we can do

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**The Patent Situation in its Relation to Industrial Development*, PROCEEDINGS A. I. E. E., May, 1909, p. 441.

this we must be more than mere engineering machines, we must be broadminded, public spirited citizens, having a general view of things in their right proportion, and not merely knowing all about technical matters and very little of anything else, and having no interest and knowledge of anything beyond our profession.

Frederick P. Fish: It is most unfortunate that engineers do not, as a rule, have the opportunity to study the great authors of Greece and Rome so as to become thoroughly in touch with them. To me they disclose a new and delightful world so different from ours that, by very contrast, I feel better equipped to understand our times and mode of thought. If the Greeks and Romans had had our literature of the nineteenth century, I doubt if they would have been more definitely impressed by the novelty and strangeness of that literature than we are by the classics when we read them.

It is a most healthful and broadening influence to become saturated with a mode of thought and a view of life so different from those with which our own experience makes us familiar. This works in many ways. In studying the life and literature of ancient times, we become more and more thoroughly satisfied as to the essential nature and capacity of man, which have changed very little during the period of recorded history, while at the same time we are deeply impressed with the different lines on which thought and action may develop in man's effort to hold his own against the forces of nature and to strive and prosper individually and in the community relation.

There is no doubt that one who studies the classics is better fitted for sane and wise views on all the social and governmental problems of to-day than would be the case if he relied only upon what he has seen or read of modern times. He surely becomes a better judge of human nature and better able to steer a straight and wise course in the affairs of life, where so much depends upon an adequate recognition of the wonderfully efficient but vacillating and unstable characteristics of man, whether regarded individually or collectively.

I feel the same as to the study of any literature of olden times. No one can become familiar with that of Iceland, Ireland, England, France, Germany, Spain, and Italy of the Middle Ages without having his views broadened and his capacity for dealing with the practical affairs of life increased. The same results follow from a study of the literature of the Oriental countries, the East Indies, Persia, Assyria, and of the early Egyptians. Folk literature, even that of savage and semi-barbarous peoples, is of value in the same way.

The great difficulty is that few men in active work have the time for such study and so much is required in schools by way of definite preparation for an engineering career that there is but little opportunity for anything that seems so remote as ancient literature. It is not worth while even to consider the study of any early literature except that of Greece and Rome, as a preparation for an engineering career, and I am very much afraid that the balance of advantage may reasonably be said to lie on the side of ignoring even these in engineering institutions of learning, that there may be more time for things directly germane to the profession. The curriculum of an ordinary training school for engineers can not be made long enough for even training in the fundamental principles of engineering—which is carried none too far—and the application of those principles to practical work.

But it is a subject for regret that engineers can not in every case have the benefit of a first-hand knowledge of the classics. Some of them get such knowledge outside of school and many read the classical authors in translations, and thus get at least a shadow of the advantage that would come to them if they were to study the original tongues. Translations, however, are unsatisfactory and do not give the spirit of the original. More than that, the mere studying of Greek and Latin as languages, is, in my opinion, of far greater value than is perhaps generally recognized at the present time. Personally, I owe more to the work I did on the classics than to any other branch of my education. I agree that the same advantages do not come from the study of modern languages, but am not certain that under existing conditions I should go so far as to advise the elimination of those studies from the curriculum of a technical institute.

C. A. Adams: I wish to refer particularly to one sentence in Mr. Dooley's paper:

> The development of the boy and not shop production should be the watchword of the apprenticeship department of every company.

That is, in a way, a new attitude on the part of manufacturing companies. For many years they have been extremely interested in the efficiency of machinery, and have devoted much time, effort, and money toward the development of machinery to its highest efficiency; but that most important and most marvelous of all machines called man, has been for the most part neglected. It is refreshing to see this further indication of the modern trend towards a more intelligent and ideal coöperation.

In regard to Dr. Steinmetz's paper, I must confess to mixed feelings which are difficult to express satisfactorily. I have the greatest sympathy with Dr. Steinmetz's general point of view. I believe thoroughly in the value of a careful study of the classics for engineers as well as for men of other professions, but I cannot believe that this study is as vital as here described, or that it accounts for the difference noted between engineers and so-called " men of affairs." Is not this difference due rather to the fact that the *average* boy who selects engineering as a profession does so because his interests are more largely objective? He is more interested in things than in the money that can be made out of them; he revels in the laws of nature and in their application to the solution of material problems, rather than in the complex human relations involved in the work of men of affairs. Sometimes too he may look about him and realize that many of the most successful men of affairs are successful because *privilege* rather than *principle* has been their motto, and that many of the now complex social and economic problems would be greatly simplified, were principle to prevail.

I do not wish to attempt any general comparison of these two types of mind, but rather to point out that they do exist; that their differences, due partly to inheritance and partly to early environment, are ordinarily not much influenced by the study of classics or by the absence of such study; that there is a place and a work for each type, and that it does not necessarily follow that one is higher than the other. The ideal education is that in which each type has full and free opportunity to develop naturally toward its maximum of usefulness and efficiency.

One other opinion that I wish to express is that the work and training of the real engineer are such as to fit him peculiarly for the solution of those numerous troublesome social and economic problems which are so much with us to-day. The work of the real engineer forces him to think clearly and accurately, knowing that he is to be judged not by men but by the results of his work as determined by the operation of invariable laws. He is thus more likely to acquire the habit of seeing these problems without bias of person or class and without the influence of custom or tradition; in other words, he is apt to be more fair-minded than the average man of affairs.

Anyone conversant with easily obtainable facts and statistics in regard to social, political, and industrial conditions in this country to-day, must certainly conclude that there are many legalized sources of unfairness which could be easily removed were it not for the tremendous influence of their beneficiaries, many of whom are men of affairs. I for one am of the opinion that the real engineer will have at least his full share in the removal of these sources of unfairness.

Farley Osgood: The thing that concerns me most is that apparently engineers are being trained for manufacturing or designing purposes only. As yet I have heard nothing of what happens to the young engineer who goes directly into the operating company. The engineer's training must be specific. He must be a specialist. This is desirable, as Professor Adams has said, if he is going to be strictly and only a manufacturing or a designing engineer.

As an operating engineer I can say our greatest difficulty is to get a young college-bred man with a technical training who can think; he can figure, but he cannot think. I agree with Dr. Steinmetz that in order to make a young man think he must be broadly trained. If a young man has a certain ability he can learn mathematics; he can use the slide rule; he can deal with definite things without great difficulty. But problems that confront the operating engineer are unexpected; they come rapidly in quick succession; they may be of an entirely different nature one moment from the next. The operating engineer, primarily and forever must be a quick and a correct thinker.

I cannot agree with Professor Adams that the narrowing down of a man's training is healthful for him, if he has to deal with broad and general problems. Mr. Fish certainly strikes the keynote in saying that young men upon graduation should be able to solve a given problem without difficulty. Without meaning in any way to cast reflections on our designing engineers, I must say that they do get into ruts. There is no question about that. They are so anxious to get ahead of each other in their line of competition, so anxious to become well-known specialists in various lines, that they seem to forget there is anything else going on in the world besides the designing of the particular type of apparatus to which they are giving their time. From the beginning the operating engineer has not only engineering problems to take care of but he has to meet the public; he has to handle the financial side of his problems; and finally, but not by any means the least of all, he has to put his subject in such a manner before his board of directors that they will give him money to spend for the benefit of the stockholders. I do not think that distinct training solely for mathematical or strictly engineering lines will help him in the final and last problem, which is to get money from people who do not understand the engineering business to put into that business. That is the most difficult problem, and the ultimate problem, of the operating engineer.

I see a good many of the young fellows when they graduate from college and make application to our company for employment. We have what we call our kindergarten course, and put the embryo operating engineers through an operating training. This course is not like Mr. Dooley's course, which is exclusively for manufacturing purposes; it is of the same general nature, only along operating lines. Every recently graduated engineer that I have met within the last five years, with very few exceptions, thinks that he must go into the factory. His whole desire seems to be to know how to design and make machines. That is certainly advisable; he must know that at some time or other. But this tendency works hardships for the operators, in getting young men that are willing to tackle the general problems of commercial engineering or business engineering as soon as they get through college. My only explanation of it is that they have not been sufficiently broadly trained to think on general subjects. They feel insecure in taking a position that will make them think of a great many different things at once which have not come to them before, therefore they go to the manufacturing companies. Frequently after they have been with the manufacturing companies for some time they begin to realize that there are other things in the world besides making machines, not the least of which is how to use them. Many of the men who go to the large operating companies come to us as graduates from the courses of the manufacturing companies. This means that a man is graduated at college, at twenty-one; and by the time he gets through the students' course in the factory he is twenty-four or maybe twenty-six years old. He has lost four or five years' training which he would have gotten if he went directly to the operating company from college. If they went directly to the operating company I think they would get on faster and be much broader men at an earlier age.

M. G. Lloyd: I am impressed with the truth of what Dr. Steinmetz brings out as to the broadening effect of the classical studies, and I think we should endeavor to have that broadening influence applied to all our young men. The condition that he mentions is not at all peculiar to the engineer but is general among American men, and furthermore, it is extraneous to the technical part of the engineer's education. On the first point I need not dwell. As regards the second point, I think, in the first place, that languages, not only one's native tongue, but foreign or even dead languages, are subjects that can be taken up very early in a child's education. They present no difficulties that a child cannot successfully master. I think that these things should be taken up. not in our colleges, but in our primary schools. The scientific studies are too exacting to be begun early. Our curricula should be shifted so as to put down languages and kindred studies and put up the scientific studies. There is too great a tendency nowadays to bring science into our lowest schools, where the children are not ready for it and cannot appreciate it, and often cannot comprehend the principles involved, especially where they are not presented by a capable instructor. The study of literature can be taken up in more mature years, and much more easily, if the child has had an early training in the language itself.

As regards the relative merits of the dead languages and the modern languages, I am not sure that I agree with Dr. Steinmetz. I think that as much broadening of the mind and as much deep, philosophic thought can be obtained from the study of Chinese literature; for I understand that men like Confucius, were great thinkers and good writers. I think this breadth of mind can also be obtained from the study of many modern European languages.

I want to emphasize that the student should acquire general culture before attending the technical school; in the technical school his attention should be concentrated upon his technical studies. His technical training should be, of course, as broad as possible; it should include operating as well as designing engineering, and any other aspects of the subject that can be handled. I would emphasize further that the actual broadening value of any study depends not so much upon the study itself as upon the way in which a study is presented. There are numbers of instructors in the classical languages who do not have the slightest broadening effect upon the students, simply on account of the way in which the subject is presented. On the other hand, a well trained instructor can, in discoursing on even a technical subject, treat it in such a way that the student will be led to look upon it broadly, and at the same time be taught to view in the same way the other aspects of life. It is the personal contact with the instructor that counts. As I look back over the educational period of my own life I feel this very deeply—the training that helped to broaden my mind did not depend upon the particular subject I was studying, but largely upon the man under whom I studied.

John C. Parker: The profession owes a considerable debt to the men who are doing the work Mr. Dooley has told us of, in training non-technical men. The actual operation of this training may be local; the significance of the thing is not local, it is not vocational; it is work which is both national and vitally human.

In Mr. Dooley's modesty and generosity toward his students I think he may be doing himself and his collaborators some slight injustice. All of us who have had to do with educational work know how hard it is to keep students up to the mark. It must be particularly hard in teaching night school. It boots nothing to say that these students are the most ambitious among the men who are working hard in the day time. Of course they are, they would not undertake the work if they were not; but I have found by conversation with men who are carrying on this class of work that many of the young men who have all sorts of laudable ambition and who undertake to piece out their daily experience by definite educational processes in the evening, enter the work under a mistaken ambition. They expect to reap an immediate reward. When the period of disappointment comes to the student, it must work hardship for the teacher. Even with the fellows who are not disappointed the teachers must find that after 9 or 10 hours in the shop it is pretty hard to hold their interest and attention. The teachers too, have been working during the day time, and at night they are called on to use the utmost tact and judgment in bringing to the students under their care the real utility of the work.

D. B. Rushmore: What is education for, or what are people after when they seek to obtain an education? At a recent meeting of the Schenectady Section, Dr. Raymond of Union College said he had come to think that the object of life was to be an electrical engineer. He thought perhaps there might properly be introduced into it one other object—that the object of life was to live, and one idea of education was to teach men how to live. All of us have to give attention to other matters besides electrical engineering. One thought that is perhaps expressed more frequently than others is the elementary law of life—that a man's first object is to obtain a source of income. A man has to be an earning power for himself and for those dependent on him. That is the first requisite; possibly that has led to a mistaken notion that that is the only object, which it is not. Apparently, however, it is the first object of our existence. Therefore, our education, whatever else it may be, must be such as to provide for that. A part of our education should, I believe, consist in teaching us subjects which may be turned to practical use as a means of subsistence.

In our capacity for earning power we have to deal with the fact that education is not through when we leave college. I think we have to keep at it through life. In judging a college education, we are only considering the base of the pyramid. We wish to build to a maximum height. If we build that base broadly we may not in the future reach a very great height. Nor, if we build on too small a basis is the structure likely to be very stable, and therefore we shall fail in the same way. Just the right dimensions to build is probably impossible to state, and must be determined as the result of judgment and experience.

Mr. Osgood brought out the interesting point that not all engineers are manufacturing men or college professors. There are many people to whom, from the purely monetary standpoint, it is desirable to leave engineering work and to associate more directly with mercantile life.

A man cannot travel in a great many different directions, and travel very far in any one direction; and if he is going to be throughout his life an engineer, who is going to use scientific facts and to some extent theoretical work in his advancement, he must confine himself to somewhat narrow lines. The culture of general education is something we all desire: it is a source of regret to feel that many of the intellectual pleasures of life must be passed over. We find that a certain percentage of our efforts, whether 50, 60, or 75, whatever it is, must be directed along purely scientific lines in engineering work. How shall we divide the other percentage which deals with influence in the family, social and political life, with the general work we should all like to do in the uplift of humanity—that is something we have to decide for ourselves.

Clayton H. Sharp: These papers and the discussion on them have brought out the situation in respect to engineering education. It is shown that we need in engineering work men of various sorts and degrees of educational training. We have heard of the man who takes an apprenticeship course, and his educational training is ended with the close of that course. He becomes a skilled workman of some kind, indispensable in the engineering field. Another man extends his course by taking night school work, thereby getting a larger theoretical knowledge of his subject. He becomes a man who is valuable in some of the higher grades of engineering work. We also have the graduate of the technical school who has devoted 4 years exclusively to the tasks set by a university or a college. His theoretical training is presumably better and more complete than that of the man who has had only 4 years in a night school. Perhaps his practical training is not so great, but in the long run—and not a very long run either—we should expect the college-bred man to excel the other in point of position and standing in his profession.

Dr. Steinmetz contends, however, that in order that an engineer may reach his complete development, not only as an engineer but also as a well trained leader of thought and of progress, he must have something besides this engineering training. He must have a liberal education. However, we may not agree with Dr. Steinmetz that the study of the classics is the one, or even the best way in which to obtain this necessary cultural education. The study of the classics is of undoubted value, having been tested during all the years which have elapsed since the revival of learning. However, it is quite possible to overrate the value of the study of Greek and Latin, particularly as at present pursued, and, as I understand it, Dr. Steinmetz does not defend the ordinary methods of teaching these languages and the literatures which are expressed in them. I believe that an insufficient time devoted to Latin or more especially to Greek is, as far as cultural results are concerned, time merely wasted, since no mastery of the language such as is necessary for a true appreciation of its literature is gained thereby. To understand the genius and spirit of the literature of ancient Rome, it is necessary to be able to do more than painfully pick out a translation of the *Commentaries of Casear* or of the *Odes of Horace*. We should read a literature in a familiar language, preferably its original language, but we do not appreciate literature when we must translate it. That means a mastery of the language. I believe that, as ordinarily pursued, students do not obtain such a mastery of Latin or of Greek, and that consequently one end which is sought, namely, the absorption of some of the spirit and ideals of ancient people, as expressed in their literature, is missed. The resultant advantage which we obtain ordinarily from the study of Latin and Greek and which is by no means inconsiderable, arises from the mental discipline thereby undergone, and the knowledge acquired of the structure and vocabulary of languages which are fundamental, inasmuch as they underlie a large portion of our own language and a large percentage of the languages of modern Europe.

I believe the same thing applies to the study of the modern languages. The technical colleges at the present time commonly require a certain amount of modern languages for entrance, and introduce a certain amount of study of modern languages during the course. In my experience I have found very few graduates of technical colleges who can pick up a piece of French or German literature, and make anything out of it at all. They stand exactly where I do in regard to the lines of Homer at the end of Dr. Steinmetz's paper: I can read them through, but I do not know what they mean. Now, if the modern languages are to be pursued, they must be studied thoroughly enough to give a mastery of the language which will enable the student to make some use of it, at least to bring him to the point where he is not afraid to tackle the language when he wants to get at some information which is conveyed in it.

To reach the highest development, in the engineer as well as in the man, he must be liberally educated. That education necessarily involves the study of some languages, but it must also include some other things. He will need to know something about the history of the rise of the modern world, as well as that of ancient institutions, of the fundamental principles of sociology, and of the rise and present character of our legal institutions. The study of the history of the common law of England and this country is of the greatest educational value. The history of philosophy is not to be ignored; it is important as presenting an entirely different point of view from the one which he will later obtain when he comes to study the exact sciences in connection with engineering work. All these go towards a liberalizing education which, with Dr. Lloyd, I believe must precede the other. However, when it comes to carrying out these ideas, we are confronted with just the same difficulties with respect to cost that we are confronted with in many engineering problems. It certainly in many cases does cost too much to go through such a course of study as this, and it is impracticable to carry it out. However, I think the best engineering schools are looking forward to the day when they can do what many of the schools of medicine and of law and of theology do, and take only men who have been graduated from a liberal course, preferably a four year course, give them the necessary scientific and engineering training, and turn them out with the degree of doctor of engineering. An engineer who has been graduated on that basis is immediately put on a rather different plane from the one who has taken the courses which are of a purely engineering nature. If we are to have great men of leading and of light in the engineering world in the future, I believe they will be, to a large extent, men who have been through a course of this character.

Jas. G. White: This subject is one of such fundamental and universal interest that I can scarcely refrain from expressing one or two opinions. There is an unquestionable advantage in having these two papers presented simultaneously, and in seeing what we might call the Alpha and Omega of the education of the engineer presented from two opposite sources; one covering such general education as may be added to the ordinary mechanic's and tradesman's training; the other advocating that broad, liberal, and almost universal education, which can be attained only by a very few. Probably all of us realize that such master minds as those of Mr. Fish, Dr. Steinmetz, and Professor Karapetoff would be broadly educated under whatever circumstances they might be trained, and wherever their lots might be cast. Most of us, however, are not blessed with such ability, and it is impossible to cover so large a portion of the field of education.

Even Dr. Steinmetz can cover only a small fraction of the world's knowledge to-day, and most of us must be satisfied with a much smaller fraction of that knowledge.

I believe thoroughly in a study of the classics, and I also firmly believe that this is possible for every engineering student, whether of Mr. Dooley's school, or of the sort that Dr. Steinmetz advocates. My suggestion as to the solution would be that the study of classics may be done, at least partly, in one's own language. We can study the classics of English literature, at least, and the student of Mr. Dooley's school can get real benefit from them. I quite agree with the previous speaker that Latin and Greek, which are alone considered classics in a narrow sense, are of comparatively little value as taught in the majority of universities and colleges. Instead of imparting a training in mental facility, the training is largely a matter of thumb facility in handling lexicons.

I am reminded of a remark made by the Rev. Dr. Boynton. In speaking of the Cornell spirit, he said that Harvard stood for style, as ordinarily interpreted by college men, Yale stood for pluck, as claimed by Yale men, and that Cornell, as he understood it, stood for work. Dr. Boynton said he was prepared to acknowledge that Harvard stood for style and Yale for pluck, and he was also prepared to admit that Cornell stood for work. But, he said, he came from a little freshwater college that many people seldom heard of, a college that he thought stood for something that he had not heard mentioned during the evening, and that was for education. That college was Amherst.

In this discussion regarding the classics I would stand for English primarily. I would like, in arranging curricula, to see more emphasis laid on training in English. This would certainly be very useful to Mr. Dooley's students. In studying the best English authors they can learn to acquire a knowledge of English which will be commercially useful, and at the same time they can learn something of the humanities and something of the philosophical side of life. The essential elements of an education as they occur to me at the moment are: 1. To learn to think. 2. To learn to express one's thoughts. 3. To acquire a fundamental knowledge of the general principles of underlying foundations of the work one expects to do. 4. The ability to find information required in connection with the solution of any problem which may be presented, and to put that information into presentable shape, and to reach a correct solution. 5. The ability to apply this general information in a commercial way.

While the study of Latin and Greek may help us to use correct English, there are many other subjects which are quite as useful, and perhaps of even more value. If we could all have the ideal education, it seems to me that it would include learning, as children, to speak two or three modern languages, which can be done easily. If children play with other children who speak foreign languages, they acquire these languages without apparent effort. If they have a nurse or nursery governess who speaks a foreign language they quickly acquire a foreign language in the same way, but the ordinary engineer is not fortunate enough to be able to have had these facilities.

I believe that a study of Latin, such as is required for the ordinary college entrance examination is very useful as an aid in understanding the derivatives of many English words, and at the same time an excellent mental training, and that, added to such knowledge of Latin, one should have if possible, a speaking knowledge of French or Spanish, or both. Practically a knowledge of Spanish is of much greater value to the American engineer than any other language. Our relations with Cuba, the Philippines, Porto Rico, Central and South America, are so increasingly important, and there will be so many more opportunities offered for business relations with South America, and other Spanish speaking countries than with other foreign countries, that I regard the Spanish language as of utmost importance for commercial purposes. Latin will help with both Spanish and French, so that a moderate amount of Latin is useful from all points of view. Then either Spanish or French, or both, can be acquired by reasonable study preparatory to entering college, if possible, keeping up such study during the college course, and later in some way getting a speaking knowledge of such languages. That can be done by residence in a country to which the language is related, or living with engineers or others who speak the language, or in some similar way. However, it seems to me a given amount of time will accomplish more for the average engineer in acquiring a knowledge of the philosophies and amenities of life, or the channels through which we can contribute most to the world, if applied to other subjects than Latin and Greek.

The general problem is: How can we apply a given and moderate amount of time to get; first, the most useful fundamental training, and secondly, the most useful fund of knowledge. For the exceptional man Latin and Greek are certainly very useful, but for the ordinary student I believe Greek should be omitted entirely, and that Latin should be encouraged only to the extent above outlined. It is fortunate for all of us that the building of the pyramid to which our attention was called by Mr. Rushmore, can be carried to considerable height, even if the foundation is narrow, and that we can from time to time build out the foundations, and build up all the courses to the top, and then add to the top. That is what most of us have to do.

I would advocate strongly the study of English continuously throughout the entire college course, say at least 2 hours a week. This study of English should in later years be a study of classical English, and of clear and explicit expression in English.

The entrance requirements mentioned by Dr. Sever might be advantageously modified by omitting the German requirement, and requiring only one language, either Latin or French. Our own language is based much more largely on Latin than it is on German—German derivations are few. As a basis of acquiring a better knowledge of English, Latin is much more useful for the ordinary engineer or ordinary man of affairs than is German. In the affairs of actual life there is not one graduate, I should say, in ten thousand who will have any occasion to use German. Furthermore, I would require a certain amount of study of such subjects as logic, mental philosophy, and principles of law. For non-technical studies we might take 2 hours of English and 3 hours of general culture subjects throughout the entire course. This would require omitting some of the more technical subjects, but if the object of education is to teach a man to think, and to teach him to express his thoughts, some of the more technical subjects can be omitted without detriment to his general education. If a young man is going into operating work a knowledge of the intricacies of machinery design is not of much use to him. It would be better if one could have a 5-year course, and spend 4 years in general educational work. including mathematics, physics, chemistry, English and general culture subjects, and then specialize as to extremely technical work in the fifth year, after the young man has chosen, to a certain extent, the direction in which his life work is to be pursued. By planning such courses, it is possible to give sufficient of the general knowledge of electricity, for example. This fundamental knowledge can be acquired without going too much into detail, or into the abstruse mathematics or theories. These advanced subjects can be taken up afterwards as one's special bent leads or work requires.

George F. Sever: The subject of technical and engineering education is so large and voluminous that it is impossible to attempt to take up all the points that have been presented this morning and discuss them to a finality. At a three days' meeting in New York last week many professors and engineers discussed quite fully the subject of the promotion of engineering education. I think there was not a single new thought presented before that meeting that was concurred in by any two men. For instance, there were suggestions for a ten-year course, a nine-year course, and then all the way down to a one-year course for the training of engineering students. The University of Missouri has established a five-year course for engineering students. Leland Stanford University is endeavoring to establish a five-year course, the idea in all these longer courses being to introduce subjects other than those of engineering. Acting on Dr. Steinmetz's suggestion, we may have to extend our courses to six, seven, and perhaps even thirteen years, in order to make a man perfect in the use of Latin and Greek.

Dr. Steinmetz and the past-president of Harvard University are certainly not in agreement. Dr. Eliot states that a man can obtain "the essentials of a liberal education" by reading five feet of books, and in that list is included all the best literature in the English speaking world, much more weight being given to English literature than to any other. I would call this to Dr. Steinmetz's attention, although undoubtedly he has already noticed it. At Columbia University in 1897 there was established a definite six-year course open to students preparing for the engineering professions. The student starts in the college and takes three years of a liberal education, which is arranged to include Greek and Latin, or any other language, philosophy, sociology, or any other subject recognized as giving liberal training. The last year in his college course includes all the subjects needed in the first year of his engineering course, so that when he receives his degree of A.B. at the end of three years he will be prepared to start in the sophomore year of the engineering course and pursue the latter for three years, and secure the engineering degree which the university gives at the completion of that course. We have thus established, and only after very careful consideration by the authorities, a six-year course, including all the so-called dead languages as well as the modern languages and the engineering training. Now, if a man enters when he is 17 years old, he will be 23 before he leaves the university, and he will have had this excellent classical training. But the question is, will he advance in the community as a high type of man more rapidly than the trained engineer who has not had this classical training? This is a subject that has been discussed many times, and we have not found that very many men are taking advantage of this six-year course, which includes all that fundamental training which Dr. Steinmetz considers the best for the rounding out of the engineer. It is my opinion, that the engineer after he has had this technical training possesses the capacity for taking up any classical language, analyzing it thoroughly and making himself a scholar outside of the university.

As a rather convincing argument for the above idea, I will call attention to a paper by Mr. Fish entitled, "Continuity of Education," in which he urges most strongly all men, engineers and others, to continue after graduation the education, and the spirit and the inspiration which they received in their college training. I think that is the time when a man should perfect himself in the classics, if he has not had them in the preparatory schools. As an educator I want to point out that Dr. Steinmetz wants us to teach Latin and Greek, and Mr. J. G.

White wants us to teach Spanish. This brings us up to the point mentioned by Mr. Osgood, that he wants men trained to manage corporations. If we continue introducing subjects we are going to have engineering courses 20 years long, and never graduate our men; and if we keep them with us too long they will become absolutely stale. We are drawn upon continually to inspire students, but like a storage-battery we get, at the end of the season, entirely discharged, and it takes a long time to get back again our inspiration to stimulate ideas in the men. We can only turn out an average product, although there may be certain stars in that product who will make distinguished successes in certain lines, but we cannot develop all the men for a particular interest. We give all the students in our engineering schools during the first year a perfectly uniform course on the engineering fundamentals, such as mathematics, chemistry, physics, drawing, etc., and in the second year they take calculus, analytical mathematics, quantitative analysis, and drawing, and other fundamental subjects. Then they begin to diverge more widely and take those subjects in the different courses which they will need in their future practice.

To accomplish this we require 18 hours of lectures and recitations per week, and oftentimes five and six afternoons devoted to laboratory and drawing room work per week. How to get in all the subjects which are considered so essential in four years I fail to see, and many of my colleagues entertain that same feeling. So that we are obliged to take the supply as it comes to us from many preparatory schools, require certain preparation for entrance, and then try to turn out the average man.

C. A. Adams: I must have expressed myself poorly indeed to be classed by Mr. Osgood as an advocate of a narrow education. This would seem particularly strange as I am now connected with and have been instrumental in bringing about the establishment of a school of engineering which requires a college degree of students seeking admission. The principal object of this plan is to encourage the laying of a broad foundation, and it is a fact that about one-half of the men seeking entrance to this school have been students of the classics, usually in their secondary school period where such study is likely to be most effective.

The point which I had hoped to make was that among the young men entering the engineering profession there are various types of mind, each with its particular field of usefulness and each requiring a different training for its best development; and that the lack of a classical training is not necessarily synonymous with a narrower education. This is much more true to-day than it was 30 years ago, owing to the greatly enlarged opportunities for the study of the literatures of other peoples than those of Greece and Rome, as well as for study in those vitally interesting fields of government, economics, social ethics, etc. I also wished to suggest the possibility that even the engineer with a so-called narrow training may prove to be a very useful citizen.

Mr. Osgood's remarks concerning designing engineers and the study of design show that he has in mind the routine mechanical computer and not at all the real designing engineer. I am particularly interested in design problems and use such problems in my teaching work, not because I expect to make designing engineers out of all my students (since I know that only a small percentage of them follow this line of work) but because such problems, carefully followed up, seem to offer one of the best means of cultivating the habit of careful, thorough analysis of any problem presented, and the habit of clear, independent thinking, the very thing the lack of which Mr. Osgood deplores.

Mr. Rushmore made one statement with which I wish to take issue—he said that the object of education is to enable us to provide for our own existence and for that of those who are dependent upon us. That may be one of the objects, but I feel very strongly that more emphasis should be laid upon the fact that the great object of education is to develop and maintain a maximum of happiness. That maximum of happiness does not depend upon how much money we can earn, but it does depend upon whether or not we are working in that field for which our particular talents best fit us; in that field where we can contribute most to the society of which we are a part.

C. R. Dooley: The fundamental idea of the night school is to train all-round men, to make them able to use their minds and their hands, and as Dr. Steinmetz mentions in the opening paragraph of his paper, able to attack new problems whatever they may be, to solve them right, and solve them quickly the very first time they see them.

Professor Adams and Mr. Scott have both referred to the many different kinds of men, suggesting that there may be demands for many different kinds of education. With an increasing number of kinds of educational systems, the problem of early selection becomes increasingly more important. The parents, and the teachers in the common schools, should be able to direct the general trend of the higher education of children. That, I believe is the highest responsibility.

One graduate of this year's class went to one of the large traction companies in New York. I am sure he will make a very excellent operating man. I was pleased to send him out to such a promising field for his beginning. I mention this only to show that part of our work, the night school feature of it, is broad enough to cover all phases of the profession, which any student may choose to enter.

The matter of holding the boys' interest and keeping them in school is seldom thought of by the instructors. I think the success of the school is due, first, to the personal interest that the instructors have in the boys and their work; secondly to the fact that the instructors are fully informed on their subjects—the students respect the information they get as being as near as possible to truth—thirdly, which is by far the greatest reason, that the boy has worked long enough at his everyday tasks to appreciate that he needs what Mr. Osgood says he lacks, namely, the ability to think. He views life from the workman's standpoint. He knows that he needs to correlate his thinking abilities with the manipulation of his fingers. It is this complete appreciation of the situation that holds the boy down to business.

Geo. H. Gibson (by letter): Engineering projects are, and should be, undertaken primarily to serve human uses and they can be carried out on any considerable scale only by social, human means, as coöperation, conference, organization, salesmanship, and other agencies included within the scope of business and affairs. Therefore, worldly wisdom, practical psychology based on observation of and experience with human nature, is as worthy of any man's study as are steam, electricity, or steel girders.

Dr. Steinmetz directs attention to the precious records of human experience preserved in the literary productions of ancient Greece and Rome. But is he not carrying the point too far when he urges the study of Greek and Latin to the exclusion of French and German? The content of these ancient languages is available in more or less perfect English translations, and nothing more will ever be added. On the other hand, French and German literature grows day by day; and this is particularly true of technological literature which is, indeed, valuable to the engineer who is pushing ahead into new developments only so far as it is new. If one waits for it to be translated by the journals or by text-book compilers, he will remain always a year or two behind the times; and many excellent original papers and monographs are never translated.

Illustrating the value of foreign technical literature, the writer makes a practice of searching carefully the various digests and indexes, including several published on the other side, with a view to catching all new developments in certain lines. It is his experience that the amount of original information appearing in the German and French engineering journals is at least equal to, if not greater, than that appearing in the English and American engineering journals.

This is especially true as to lines that might be classified under mechanical engineering, including, for instance, such subjects as steam turbines, high-pressure and high-efficiency centrifugal pumps and blowers, chemical processes for water purification, heating and ventilating practice, steam condensers and accessories, etc.

This may be due to greater activity in research, or it may be due to less reticence among investigators on the other side in giving results to the public; but nevertheless the fact remains that if the specialist wishes to keep up with the month-by-month progress of his line—and in many lines innovations appear in such rapid succession that that is commercially essential—he must read the French and German technical papers or else have them read for him as they appear.

As showing how incompletely the "state of the art" is presented in American technical periodicals, only recently the writer came across an article in a French journal summarizing the latest developments in steam condenser practice in both Europe and America. This article not only covered some recent and very ingenious condenser work done in Europe, but also gave the gist of the more important patents taken out in the United States. It contained, therefore, much information that so far had not appeared in our own papers. So by carefully following these foreign papers we are better able to keep in touch with what is going on next door. The most satisfactory way of doing this is to read or glance through the articles one's self rather than to trust to translations or abstracts. In order to do this one must read French and German, which therefore have a practical value to the engineer that Mr. Steinmetz would seem to deny to the modern languages. Further, it is the writer's experience that in reading on a subject with which he is somewhat familiar the difficulties of a foreign vocabulary are greatly minimized and that, therefore, the acquaintance with a foreign language which can be obtained in the usual college course will serve to good purpose. The technical terminologies of French and English for example, are largely identical.

A. E. Kennelly (by letter): While wishing to endorse what Dr. Steinmetz has said about the value of the classics and of ancient languages in education, I think that he hardly does justice to the corresponding value of modern languages, and I submit that these also have claims to be recognized.

It is, perhaps, open to debate whether the modern languages of Europe offer so great a range of variation in mental perspective, or in the working philosophy of life, as do the classics; but it can hardly be doubted that in ideality, poetry, humor, and subtlety of intellectual discrimination, the languages and literature of modern Europe are on equal terms with the languages and literature of ancient Greece and Rome.

Moreover, I submit that no education can claim to be liberal which does not give to the possessor at least a reading knowledge of one modern language besides the mother tongue.

H. W. Fisher (by letter): I feel that my Greek and Latin have been a help to me in many ways, but I think more practical good might have been obtained had I spent less time on them and more on English. Once I heard a paper read before the Engineers' Society of Western Pennsylvania, the style of which was so noticeable that afterwards those present, as if by common consent, made special mention of the author's diction, although, from the engineering standpoint, the paper was of a high order.

I believe that our engineering colleges should accumulate a library of papers of this kind and require the students to make a special study of them at some part of the college course.

During the last two years I have become interested in the international language Esperanto. In it I find much that is most valuable in giving me a clear and logical idea of grammar, of language, and how idioms should be translated, etc. Now that this language is being adopted so largely by international societies and is being taught in so many schools, I believe that at least one year of Esperanto previous to the study of other languages would be invaluable as a mental drill, and would acquaint the students with the fundamental roots of Latin, and the most important European languages. Afterwards he could use Esperanto in conversation, or correspondence with foreigners, which I have done, much to my personal satisfaction.

J. Dalemont (by letter): The paper by Dr. Steinmetz shows the importance of the question of classical education for engineers. The same question has been agitating the minds of Europe for some time past, particularly in France and Belgium, where there is a tendency to cut down the time devoted to the study of dead languages. This, however, should not be used as an argument against Dr. Steinmetz's contention, as it is quite possible that in these countries too much time has hitherto been given up to the classics.

There are two points on which I think most people will agree, namely: 1. The elite of all cultured classes in any country should receive an intellectual training, which will allow them to meet on common ground, when discussing social, economic, and political conditions.

2. The engineer, of all men, can least afford to ignore social problems, because of his responsibilities, which are often greater than those of most men, and of the far-reaching effect of his work, but particularly, because of his close connection with industrial activity, which is becoming more and more the centre of modern life.

From these two fundamental facts we may conclude that the training of the engineer should have something in common with that of the other professions. As all high intellectual careers suppose a special higher education, it is to the college that we must look for some method of exerting on the mind of every student the same general influence; and in order that his mind shall bear this universal stamp, the question of the choice of the studies imposed on him by the college curriculum becomes a very important one.

It remains to be considered what studies are especially adapted to the formation of the judgment in considering social conditions. It cannot be denied that an adequate knowledge of ancient civilizations tends to develop an observant as well as a philosophical mind, two qualities of especial value in a close study of modern life. It is this disciplinary training of the mind which will enable the engineer to assume in society the place which Dr. Steinmetz would have him fill.

But we may here ask if it is advisable to exact that such studies be pursued by all students in the Greek, Latin, or other dead languages. It has often been held that as far as the training of the judgment is concerned, a study of these ancient civilizations through the medium of translations is as beneficial as if made in the original. It seems to me, however, that the study of ancient languages is most beneficial to the mind and may be considered as the starting point of all high intellectual culture. If colleges were frequented exclusively by the intellectual elite, it would be an easy matter to decide upon a curriculum which would be suitable for all. But such is not the case. Very wide indeed, and justly so, are the roads leading to a college education, and the elite—based solely on the result of work and effort, in accordance with the requirements of our modern spirit and the interests of society at large—is the outcome of a slow process of selection and elimination among the thousands of young men who yearly set out on these roads. Here arises the real difficulty in deciding this question of the humanities.

Should every student be required to follow a course of studies which would be of benefit only to the few making up this elite? Certainly not. The course of study should not be chosen for the latter only, but should be adapted to the needs of every student—whatever career he embraces. In retaining the study of the classics, therefore, some effort should be made to modernize the system of teaching them, so that they may be of benefit in preparing the mind to face the requirements and responsibilities of modern life. To my mind, a college course should not be considered as an immediate means of making a livelihood, as such a mission belongs more properly to the professional course.

The foregoing remarks are in no way opposed to the principle of classical education; they are merely intended to call attention to the fact that the studies in connection with such an education should be kept within certain limits. If at the present moment there is a desire in Europe to curtail the study of dead languages, it is because that country is suffering from too great a development of classical education. It must be remembered that the study of the classics, like the study of the positive sciences, will not only impart a certain knowledge, but will moreover determine a certain mentality. The mentality of the poet is not that of the business man, while that of the scholar is not exactly that of the engineer. They may have certain points of resemblance, yet the differences between them will not allow of their being formed in exactly the same mould or in the same intellectual atmosphere.

To sum up, if the advantages of the classics and the necessity of teaching them are incontestable, it would, on the other hand, seem injudicious to impose a classical course on all students indiscriminately. It might be beneficial, as is done in the colleges and lyceums in France, to allow the student the option among several combinations of studies, or again, as in the German universities, to allow him a certain liberty in choosing some of the courses which he is to follow.

Ralph D. Mershon (by letter): I entirely agree with Dr. Steinmetz that breadth of education is desirable. I agree that the study of the Greek and Roman civilizations will conduce to that end. But I do not agree that the study of Greek and Latin constitutes the most effective means of arriving at breadth of training or that such study will, in itself, lead to knowledge of the Greek and Roman civilizations.

The "average man" (that mysteriously elusive individual with whom we must necessarily deal in such discussions as this) who studies Greek or Latin, or at least the average American student of these languages, is kept too busy struggling with the intricacies of the language itself to get much appreciation of the subject-matter of the text. Such mastery of the language as he may achieve in a college course is not sufficient to make it an adequate vehicle for beauty of sentiment or depth of thought. Such appreciation as he attains of the art and literature and such knowledge as he acquires of the philosophy, religion, and politics of the Greek and Latin civilizations come through studies supplemental to that of the languages; studies pursued in English and which could be just as well pursued without any reference to the Greek and Latin languages. The truth of this may be easily verified by comparing notes with those whose college courses have been along classical lines. That it should be otherwise, would mean the study of these languages to an extent hardly expedient for the average man, certainly not expedient for the engineer. This being the case, the broadening influence of Greek and Latin is confined, mainly, to the discipline resulting from the study of language as such.

In general, it seems to me much better to get the discipline through the study of modern languages, mathematics, and such other subjects as will give it and in the end leave the student with an equipment of value to him in after life—of much more value than Latin or Greek could possibly be. Such study, accompanied by studies in English bearing upon the Greek and Latin civilizations, would accomplish the result aimed at and in a manner much more satisfactory and expeditious than the study of Greek and Latin. This course is especially expedient in the case of the large majority of American technical students, who are limited as to means and must make every minute devoted to education count for its fullest worth. For those who are so inclined and have the time and means at their disposal, the study of Greek or Latin, or music, or art, or any other study the pursuit of which may be considered rather as a luxury than as a necessity in the matter of breadth of training or of utility, would be a highly delectable preliminary to an engineering education; and advisable, if the individual be of a grain to take so high a polish and still be effective in the daily grind of a useful life.

The utilitarian advantage mentioned in the paper as incident to the study of Greek and Latin; namely, that of easy comprehension of scientific terms, is of considerable moment only in special cases; but even then it would hardly justify the immense amount of time such study entails. I fail to see why it would not be better to expend the time necessary to the memorization of the comparatively few terms employed in science rather than the vastly greater amount of time necessary to memorization in the study of these languages.

I know one engineer in whose experience such " small Latin and less Greek " as is his portion has been of little value; while his experience with French, the only modern foreign language he has studied, is quite contrary to that ascribed to modern languages by Dr. Steinmetz. His French has helped him in engineering work (and otherwise) in spite of the lack of practice, because not all foreign works of value are translated into English, or, at best, tardily. He has found scientific French easier than any other kind, in spite of the technical terminology and this, I believe, is the experience of most other students.

Dr. Steinmetz speaks of the value of a broad education in fitting the individual

> To perform his duties as a citizen of the Republic during the stormy times of industrial and social reorganization which are before us.

Here again I am in sympathy with him as to the end, but not entirely as to the means. Anything which may contribute toward each taking his proper and intelligent part in the change which must come, is to be ardently desired. The first essential requisite to this end is not broader training, but utilization of such training as may now be had. Until the intelligent men of this country, until the engineers—since we are addressing them—realize that they have civic duties and will conscientiously attend to them, each to the extent of his ability, increased breadth of training will not accomplish much in increasing the efficiency of citizenship. Until engineers shall cease to be too busy to attend to such duties; until they are willing to give to them some measure of the attention and thought they would devote to an engineering proposition; until they come to consider them duties in the full sense of the word, instead of evading them and taking a sneaking pride in such evasion; little will be accomplished in bettering citizenship no matter how education may be broadened. When such a change of mental attitude has been wrought, broader training as improving citizenship will be effective, and not until then.

After all, I question whether breadth of mind and independent thought are not more effectively fostered in the student by breadth of mind in his preceptors than by any special course of study. A course of study, in itself of the narrowest kind, may be made broad by the administration and direction of a broad mind; a mind from which the student will unconsciously absorb that which will influence him to larger reading and thought during his college course, and give him such an impetus in this direction as will persist after he has left college. For breadth of training cannot be attained in the brief span of a college course, any more than can the mastery of any given subject; and the college course is, at best, but a preliminary training and guide to the later self-training and independent thought, leading to the desired end.

There are a number of other points in the paper open to question, such as the definition of education; the sweeping implication that engineering is the application of empirical science; the implication that the engineer is limited to a single vocation, and the statement that this vocation necessarily tends more to onesidedness than the vocations of men in other callings. But these are points beside the main issue.

The paper appears to me inconsistent, and to one unacquainted with the author might appear pedantic, in that, although addressed to those having presumably no knowledge of Latin or Greek, it contains a number of Latin and Greek citations and allusions, and ends with a Greek quotation.

C. P. Steinmetz (by letter): I am glad to be able to agree with most of the speakers, even with those who can find no use for the classics in the training of the professional electrical engineer. We do not need the classics if we take the narrow view that the purpose of the college is to train the human animal to perform the functions of a professional electrical engineer, just as we train some wild animals to perform some other functions or tricks. But in this case we should stop talking of college graduates as educated men. What I was aiming at was the education of the intelligent being to perform the duties of citizenship in the field of the electrical engineer.

If we desire to train boys to be professional electrical engineers then naturally, no matter how much we lengthen the courses, we cannot expect to produce at the same time competent designing engineers and operating engineers and consulting engineers and corporation managers and constructing engineers and commercial engineers, etc. That is not what I desire. It is not what Mr. Osgood wants, as I understand him, to have the college turn out operating engineers. What he complains of is the rather insufficient development of common sense and ability to think in the product of the present college, which results from the narrowness of the professional training. It is this defect which I desire to obviate by advocating a broadening of the education.

Mr. Rushmore has well expressed the purpose of education as being for the purpose of teaching the boy to live; that is, to get the highest satisfaction out of life in its relation to the human race at the present time, and the human race of past ages as recorded in their literature, their work, etc., and the relation to the future of mankind, the work and the life of the human race in the future. For this purpose it is necessary to teach him to earn money. To live satisfactorily we must have money. The earning of money is the means but is not the purpose of life, and I consider it as the great fault of our present age, and especially of our nation, that we largely mistake, in this respect, purpose and means. And just here a retrospection into ages where a clearer view existed on the relation of the purposes of life and the means of living, where money was not the standard of success, is especially beneficial.

In my paper I have attempted to outline the situation and to suggest one remedy, in the study of the classics. I do not desire to say that is the only one. There are other factors contributory to that broad education. To mention only one, since its educational value is frequently not realized—college athletics. I have not attempted to suggest methods of accomplishing the result, because I believe that the means of broadening the education will be developed with increasing rapidity by the acceleration afforded by the pressure from within and without the engineering profession.

What I would like to see is a classical academic course interposed between the classical high school and the technical college, and then to have the college work succeeded by a year of practical experience in a manufacturing or operating company—one year of graduate work rounding off the education. This would mean 12 years from the entrance in the high school to the entrance, as master of engineering, into the profession. It is a long time, only 1 year less than that demanded by the German gymnasium and university. Very many boys could not afford it. There are many who could afford it but do not avail themselves of it; some because of the inherent desire of American boys to become independent and self-supporting as early as possible, when they lack the experience and intelligence to realize the necessity of education; others, because their parents have succeeded in life without a college education, or with a very meagre education, and do not realize that what was sufficient in former times when the world was young, will not be sufficient in the times that are coming.

What can be accomplished without greatly lengthening the course is to establish the classical languages, Latin and Greek, as entrance requirements in the school or college, devoting the time which many colleges devote to modern languages to classical literature and languages.

Coming to immediate possibilities: what I would like to see introduced; what I believe can be done immediately; what I should urge, is to recognize the classical languages as equivalent to the modern languages in the entrance to college and in college studies. That is, where one to two languages are required for college entrance, the student should have the choice of any of these five languages—Latin, Greek, French, German, and Spanish, and from these languages he should be allowed to choose those which he desires to continue in his college course, thus leaving the language study in college elective among these five languages. That can be done, and should be done immediately.

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POLE-FACE LOSSES

BY COMFORT A. ADAMS, A. C. LANIER, C. C. POPE, AND C. O. SCHOOLEY

INTRODUCTION

The object of the experiments recounted below was to establish a reliable and if possible a *rational* quantitative relation between the pole-face losses and the principal variables involved therein. The work was originally undertaken as a supposedly small part of a larger investigation without any realizing sense of the amount of work involved or of the difficulty of obtaining reliable results. Another time the method employed would be modified in the light of this experience, but although the results are not altogether satisfactory from the standpoint of the investigator, they are sufficiently accurate for most practical purposes, and it is believed more reliable than those heretofore published.

The experimental work was so recently completed that it will be impossible at this time to give the results, or their analysis. in a thoroughly digested form.

THEORY

In any dynamo-electric machine with a toothed armature the magnetic flux density at the pole-face opposite a tooth is greater than that opposite a slot, and as the armature rotates, the teeth carry waves of flux across the pole faces; that is, each point on the pole face is subjected to a pulsating flux density which gives rise to eddy currents in the mass of the pole face. Some energy is also dissipated by magnetic hysteresis, but at the ordinarily high tooth-frequencies the eddy-current loss predominates; with solid pole faces the hysteresis loss is negligible. In any case these phenomena are so complex from the standpoint of quantitative analysis that it is practically impossible to separate the two losses.

Were it not for the magnetomotive force of the eddy currents themselves the flux would distribute itself, both outside and inside of the pole shoe, in such a way as to correspond to the minimum total reluctance; that is, the flux pulsations would gradually die out and the flux tend toward uniform density in proceeding from the pole face back into the mass of the pole shoe. But the eddy currents materially hasten this equalization in their effort to damp out the flux pulsations of which they are the result. This effort to equalize the flux density is maximum at the surface of the pole shoe where the maximum pulsation takes place, and it undoubtedly alters to some extent the flux distribution over this surface.

Within the pole shoe the disturbance is propagated in the familiar manner of electromagnetic waves, the attenuation constant being very large, owing to the high permeability and conductivity of the medium and the relatively high frequency of the pulsation, the penetration wave-length being very short for the same reason.

With solid pole shoes and average constants the wave is practically damped out at a distance back from the pole face equal to about one millimeter, the pulsation being thus confined to a very thin surface layer.

With laminated pole shoes the conditions are quite different. This difference can easily be understood by reference to Figs. 1 and 2. Fig. 1*a* is a plan view and Fig. 1*b* an elevation of a solid pole shoe, together with the teeth. Fig. 1*c* shows an assumed sinusoidal flux variation at the pole face. In Fig. 1*a* approximate eddy-current paths are shown in light lines; the directions as indicated by the arrows correspond to a right-to-left movement of the teeth across the pole face. The transverse portions of the currents are the ones which produce the damping of the flux pulsations and are predominant in the case of solid shoes; they will be referred to as the *damping currents*.

With ordinary proportions of teeth and pole face, those parts of the eddy currents in the circumferential direction are relatively small; their tendency is to screen the center of the pole from the flux pulsations and to drive the latter to the two circumferential edges; these circumferential portions of the eddy currents will therefore be called the *screening currents*. With solid pole shoes the screening currents may safely be neglected.

Fig. 2*a* is a plan view of a portion of a *laminated* pole shoe showing the approximate eddy-current paths at the pole face, and Fig. 2*b* is an elevation of the pole shoe. Except for the laminations, Figures 1 and 2 are intended to represent the same conditions.

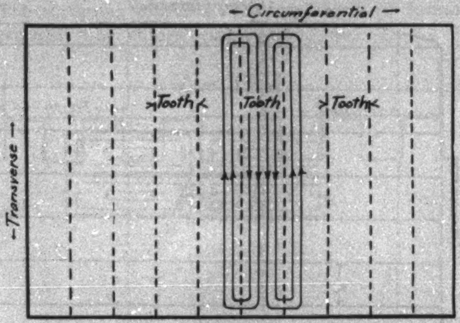
Circumferential
Transverse
Tooth
Tooth
Tooth

Fig 1a

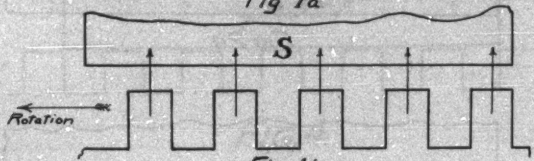

Fig. 1b

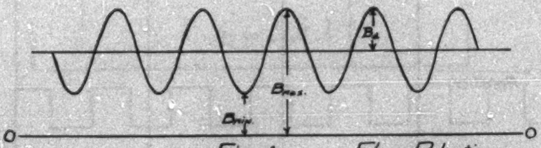
B_a
$B_{max.}$
$B_{min.}$
O
O

Fig 1c Flux Pulsation at Pole Face

In the case of laminated pole shoes represented in Figs. 2a and 2b the circumferential or screening currents predominate, and the transverse or damping currents are not only greatly reduced in magnitude but also in effectiveness; that is, the pulsations will penetrate much deeper into the pole shoe and the advantage of the laminations will be considerably neutralized.

Both the damping and the screening currents have the same origin and nature. The damping currents try to check the penetration of the flux pulsations into the pole shoe perpendicular to the face, and the screening currents tend to check the penetration of the flux pulsations into the laminæ from the side surfaces towards the center. The chief difference is that

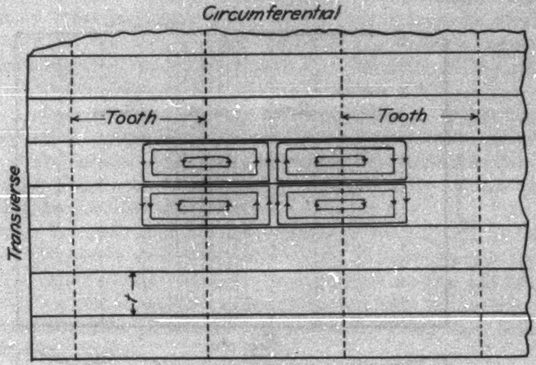

FIG. 2a

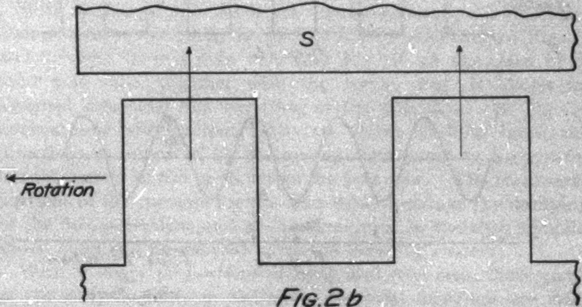

FIG. 2b

whereas the damping currents tend to force a more uniform circumferential flux distribution the screening currents tend to disturb an otherwise uniform transverse flux distribution across the section of the laminæ. Both tend to increase the reluctance of the magnetic circuit and to decrease the eddy-current loss. The screening currents, however, tend to increase the hysteresis loss, other things being equal.

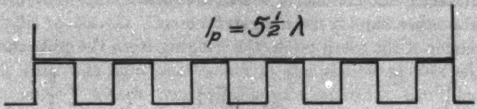

FIG. 3.

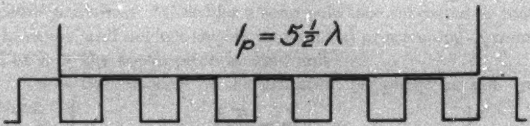

FIG. 4.

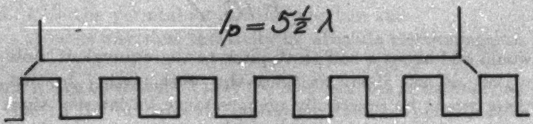

FIG. 5.

There is another source of energy loss in the pole face which is in some cases of considerable magnitude. It is that due to the *pulsation of reluctance of the main magnetic circuit* caused by a variation in the number of teeth under a pole. For example, if the pole arc (l_p) is just five and a half times the tooth pitch (λ), and if the air gap be very short, there will be positions of the armature where there are six teeth under a pole face and other positions where there are only five, there being a variation of reluctance of about 15 per cent between these two positions (see Figs. 3 and 4). Such a variation would cause a pulsation of flux through the whole magnetic circuit and a consequent loss of energy. Of course this variation could be largely eliminated by chamfering the corners of the pole shoes.

On the other hand if the air gap be larger, say about equal to one-quarter of the tooth pitch, the fringing from the pole corners would add about a half tooth pitch to the equivalent pole arc, making it just about six times the tooth pitch. In this case there would be practically no reluctance variations, since the number of teeth under the equivalent pole arc is constant (see Fig. 5).

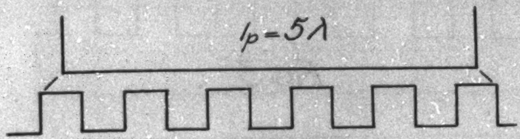

FIG. 6.

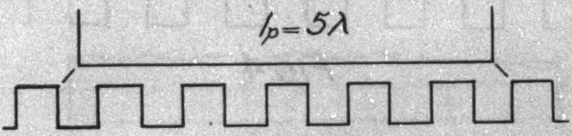

FIG. 7.

If the actual pole arc is just six times the tooth pitch, the minimum reluctance pulsations occur with a short gap and the maximum with a fairly long gap (see Figs. 6 and 7).

As an example, consider the apparatus used by Wall and Smith[1] for the investigation of pole-face losses. The pole face was solid, with square corners, and the actual pole arc was just three and a half times the tooth pitch. Thus with fairly long gaps the reluctance pulsation loss was a minimum, and with very short gaps a maximum. The pulsation was very large at short gaps owing to the large percentage of reluctance variation, probably about 25 per cent. As this part of the loss was not recognized at the time, it made the pole-face loss appear to increase with decreasing air gap at least twice as rapidly as it should have done. This entirely masked the phenomena under consideration.

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[1] Institution of Electrical Engineers, London, June, 1908, Vol. 40, p. 577.

This loss was also overlooked in the results of Dexheimer's experiments,[2] where considerable discrepancies can thus be accounted for.

Returning now to the damping currents and screening currents, these have both been analysed theoretically, but each independently of the other, the former for the case of solid pole shoes by Potier[3] and Rüdenberg,[4] and the latter for laminated cores by Steinmetz.[5]

Solid pole shoes. Consider a solid pole shoe subjected to tooth flux waves, and neglect the circumferential or screening currents.

Let λ = the tooth pitch in cm., and

v = the velocity of the armature periphery in cm. per second.

Analyze the circumferential flux distribution curve at the surface of the pole face into its fundamental and harmonics, (the wave length of the fundamental being λ), and consider separately the loss due to each.

Let B_1 = the amplitude of the fundamental pulsation, and

B_n = the amplitude of the nth harmonic.

Let μ = the permeability of the pole face and

ρ = its electrical resistivity in absolute electromagnetic units.

Then it can be shown[3 & 4] that the pole-face loss in watts per sq. cm., due to the fundamental pulsation wave, is approximately

$$P_1 = \frac{B_1^2}{8\pi} \sqrt{\frac{v^3 \lambda}{\mu \rho}}\, 10^{-7} \qquad (1)$$

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[2] "Die Gleichstronmaschine," E. Arnold, Vol. I, second edition, page 649.

[3] L'Industrie Electrique, 1905, p. 35.

[4] Elektrotechnische Zeitschrift, Vol. 26, 1905, p 181.

[5] "Transient Phenomena", p. 355.

and that the corresponding attenuation constant is approximately:

$$\beta_1 = 2\pi \sqrt{\frac{\mu v}{\rho \lambda}} \tag{2}$$

It is somewhat surprising that in equation 1 the pole face loss is proportional to the 3/2 power of the velocity (and therefore of the tooth frequency) rather than to the second power. But this is after all only reasonable, since the greater damping action at the higher frequencies reduces the equivalent depth of the active layer; that is, the attenuation constant is larger and the flux wave does not penetrate as deeply into the pole shoe.

In applying equations 1 and 2 to the harmonics of the flux pulsation, it should be remembered that whereas λ, the tooth pitch, is also the circumferential wave length for the fundamental, the circumferential wave length for the nth harmonic is, $\lambda \div n$.

Neglecting the influence of the damping currents and of saturation upon the flux distribution at the pole face, B_1, B_2, B_3, etc., are proportional to the average pole face density B and may be written,

$$B_1 = k_1 B, \qquad B_2 = k_2 B, \qquad B_3 = k_3 B, \text{ etc.}$$

Then from equation (1),

$$P_1 = \frac{10^{-7}}{8\pi} k_1^2 B^2 \sqrt{\frac{v^3 \lambda}{\mu \rho}} \text{ and } P_n = \frac{10^{-7}}{8\pi} k_n^2 B^2 \sqrt{\frac{v^3}{\mu \rho} \frac{\lambda}{n}} \tag{3}$$

The ratio of the amplitude of the nth harmonic to that of the fundamental or the per cent of nth harmonic is, $k_n \div k_1 = a_n$.

Then:

$$P_n = P_1 \frac{a_n^2}{\sqrt{n}} \tag{4}$$

and the total pole-face loss in watts per square centimeter, is:

$$P = \frac{10^{-7}}{8\pi} k_1^2 B^2 \sqrt{\frac{v^3 \lambda}{\mu \rho}} \left(1 + \frac{a_2^2}{\sqrt{2}} + \frac{a_3^2}{\sqrt{3}} + \text{etc.}\right) \tag{5}$$

or

$$P = \frac{10^{-7}}{8\pi} k^2 B^2 \sqrt{\frac{v^3 \lambda}{\mu \rho}} \tag{6}$$

where
$$k^2 = k_1^2 \left(1 + \frac{a_2^2}{\sqrt{2}} + \frac{a_3^2}{\sqrt{3}} + \text{etc.} \right) \tag{7}$$

The watts per square inch of pole face is given by equation (6*a*) where B = average pole face density in maxwells per square inch, v = peripheral velocity of the armature in feet per second, λ = tooth pitch in inches, and ρ and μ are the same as before.

$$P'' = 1.65 \times 10^{-7}\, k^2\, B^2 \sqrt{\frac{v^3\, \lambda}{\mu\, \rho}} \tag{6a}$$

Thus $k\,B$ is the amplitude of the *equivalent* sinusoidal pulsation, and the problem resolves itself into the determination of k. The k's and the a's are obviously wholly dependent upon the shape of the flux distribution curve, which in turn is wholly dependent upon b, the ratio of slot opening (w_s) to the tooth pitch (λ), and q, the ratio of slot opening to air gap (δ). Unfortunately the k's and the a's are exceedingly complex functions of these two variables, even under the assumption made above as to neglecting the effect of damping currents and saturation upon the pole-face flux distribution.

Of the two variables involved in k, b ($= w_s \div \lambda$) has for open slot machines a fairly narrow range of variation, being rarely found outside of the range from 0.4 to 0.6 with an average of 0.5.

Then if b is fairly constant, k is largely dependent upon the ratio

$$q = w_s \div \delta$$

that is, with a given value of b, k will be a function of q. As a general determination of k appears to be practically impossible, it will be necessary to consider a few special cases in order to get an idea of the nature of its variation.

For very large gaps, q is small and k obviously approaches zero.

For four other points (q = 2, 6, 12 and 24, and $b = 0.5$), flux distribution curves were carefully worked out with the aid of the experimental results of Wall.[7] These curves were then analyzed and k^2 computed according to equation 7. The resulting values of k^2 are plotted in Fig. 8.

For larger values of b, k would be somewhat larger, and smaller for smaller values of b. But within the ordinary range these differences are small.

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[7] T. F. Wall. Journal of the Institution of Electrical Engineers, June 1908, Vol. 40, p. 550.

In using Fig. 8 it should be remembered that even if the flux distributions had been determined accurately from the static standpoint, the eddy currents in the pole shoes tend to alter the static distributions at the surface in the direction of decreasing their variation. The reluctance of saturated teeth also tends in the same direction. Neither of these sources should under ordinary conditions give rise to considerable variations from the results shown in Fig. 8.

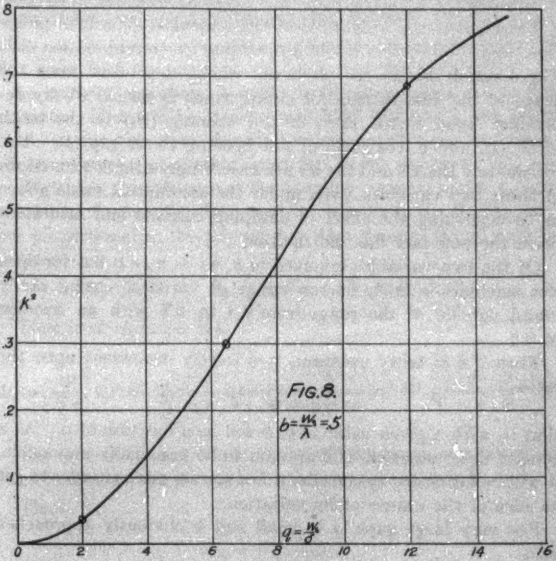

FIG. 8.

Equation (6), together with Fig. 8, thus gives a fair idea of the factors which determine the pole-face losses in the case of solid shoes.

Laminated pole shoes. Although any reasonably complete analytical treatment of this case would be extremely complex and tedious, if not impossible, it is possible with the aid of equation 6 (for solid poles) to make some roughly quantitative deductions as to the effect of laminations.

Referring to Fig. 9, assume the eddy currents to flow in symmetrical paths as shown, and consider the element *a b* of the damping current. This element experiences exactly the same electromotive force as in the case of the solid pole shoe, but the resistance of its path is $\left[1+\left(\frac{\lambda}{2t}\right)^2\right]$ times as great as for the solid shoe, where t is the thickness of the laminations and λ the tooth pitch. These damping currents will thus have the same effect with respect to those of the solid shoe as if the specific resistance were increased in the ratio $1+\left(\frac{\lambda}{2t}\right)^2$, or approximately $\left(\frac{\lambda}{2t}\right)^2$. This assumes the same quality of iron in the two cases. It will also be observed that the system of damping currents thus established does not cross the full thickness of the laminæ although the more important longer currents which flow in the longer paths do flow nearly across. The effect of this restriction in length of the damping currents is obviously to

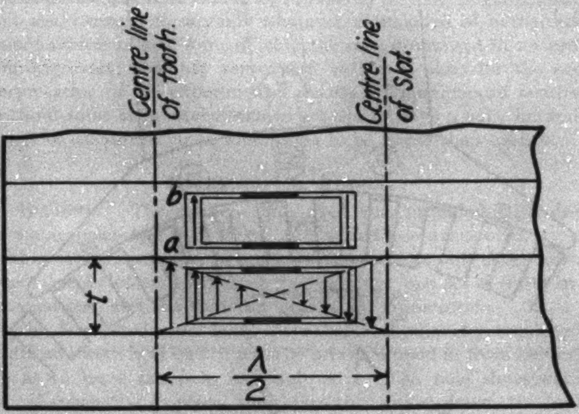

FIG. 9.

reduce the damping effect, to allow the flux to penetrate deeper near the lateral surfaces of the laminæ, and thus to increase the loss slightly.

Thus with the same quality of iron as in the solid shoes the principal effect of laminating may be represented by an increase of specific resistance in the ratio $\left(\frac{\lambda}{2\,t}\right)^2$. By introducing this ratio into equation 6 together with a constant a to take account of the shortened damping-current paths, we obtain for the watts per square centimeter of pole face for laminated pole shoes:

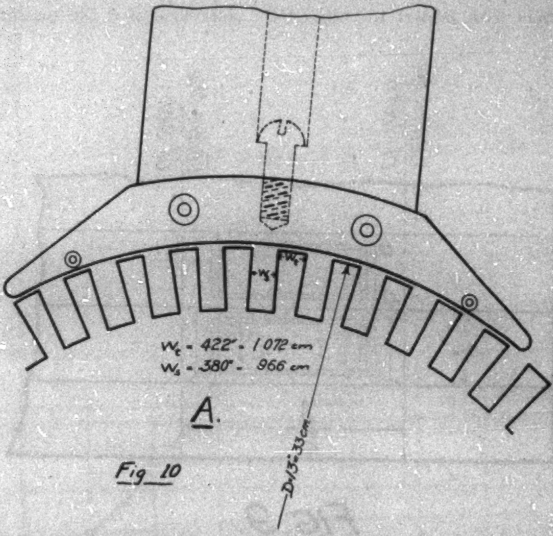

Fig 10

$$P_l = P\,a\,\frac{2\,t}{\lambda} \tag{9}$$

or $$P_l = \frac{10^{-7}}{8\,\pi}\,k^2\,B^2\,a\,\frac{2\,t}{\lambda}\,\sqrt{\frac{v^3\,\lambda}{\mu\,\rho}} \qquad 10)$$

or $$P_l = 7.96\times10^{-9}\,a\,t\,k^2\,B^2\sqrt{\frac{v^3}{\mu\,\rho\,\lambda}} \tag{11}$$

It is interesting to note that whereas the solid pole-shoe loss is proportional to $\sqrt{\lambda}$, that for the laminated shoes is inversely proportional to $\sqrt{\lambda}$.

Reduced to the same units as for equation 6*a*, the watts per square inch are:

$$P_l'' = 3.3 \times 10^{-7}\, a\, t\, k^2 B^2 \sqrt{\frac{v^3}{\mu \rho \lambda}} \qquad (11a)$$

It should be noted that perfect insulation of the laminæ is assumed, otherwise P_l will be larger.

These theoretical equations are crude, not only because of the assumptions and approximations involved in their development but also because no account whatever is included of numerous minor sources of loss, some of which become prominent in certain limiting cases; but they serve very well as a basis for the interpretation of the experimental results. Experimental results without some such interpretation are apt to have a very limited range of usefulness, or in some cases to be worse than useless.

EXPERIMENTAL RESULTS

Apparatus. The machine employed was provided with detachable poles and pole shoes, and with three armatures, each with a different number of teeth. Three sets of pole shoes were used, one set of solid annealed steel castings, one set of 0.014 in. laminations, and the third set of 0.06 in. laminations.

The laminated pole shoes were held together by insulated bolts and were held on the poles by screws tapped in from behind so as to leave the pole face unbroken. The pole shoes were bored concentric in place; they were then taken down, the tool burrs were removed, and the poles carefully replaced.

The air gap was varied by means of shims placed behind the pole pieces. As the pole face could not be concentric with the armature at all gaps without reboring for each gap, an equivalent corrected gap was computed when necessary.

The dimensions of the pole shoes and armature teeth are given in Figs. 10, 11, and 12.

The losses were measured by running the machine light as a motor, measuring the input and subtracting the other losses as below.

Constant-speed tests. The field current and armature voltage were varied over a wide range in such a way as to maintain a constant speed of 1246 rev. per min. By plotting a curve of watts lost *versus* volts, the friction loss was determined. This, together with the armature copper and brush losses, was then subtracted from the total to get core loss plus pole-face loss. By plotting core loss plus pole-face loss versus air gap and extending the curve slightly the core loss was determined. This was then subtracted to get the net pole-face loss.

Constant flux tests. The exciting current was maintained constant and the speed varied over a wide range by varying the armature voltage. The object of these tests was to check the exponent of v in equations 6 and 11.

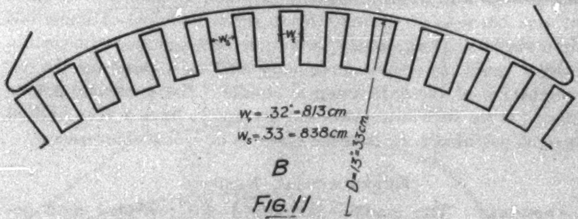

FIG. 11

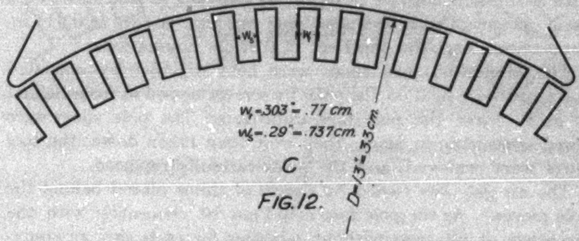

FIG. 12.

These two tests were made with numerous combinations of three armatures, three sets of pole shoes and five air gaps.

Errors. The greatest care was observed in the conduct of the experiments, the measurement of the air gaps and in working up the results; but errors undoubtedly crept in, in addition to those inherent in the method. Of the latter the following are the most obvious; (*a*) errors due to heating of pole shoes and consequent change of specific resistance; (*b*) errors due to distortion of flux under pole face by armature current; (*c*) variation of the friction loss during the test; (*d*) variation of core loss with air gap.

a. The heating element was largely eliminated by starting the tests cold and not carrying them far enough to cause a troublesome rise of temperature. Within the range of the results given below the maximum temperature variation was less than 20 degrees cent. which means about 3 per cent variation in the pole-face loss, since the specific resistance enters equation 6 as the square root.

b. The distortional effect is negligible except for short gaps, being much larger of course for the solid poles and least for the 0.014 in. laminations. But this error becomes rapidly a serious one when it once begins to count, since it means an increase in armature core loss, which increase—by the method of elimination already outlined—appears in the pole-face loss; thus the apparent pole-face loss is doubly increased. This effect results in raising the apparent exponent of *v* and of *q* in the loss equation.

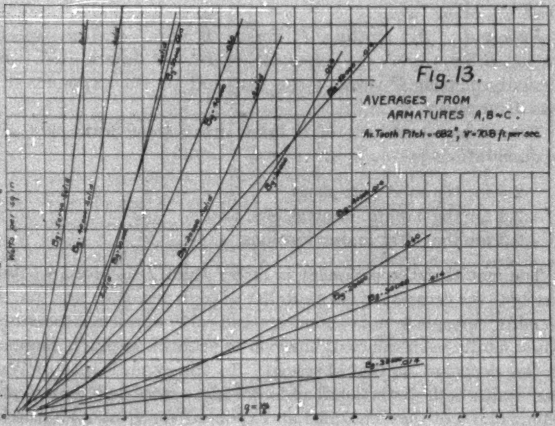

Fig. 13.

AVERAGES FROM ARMATURES A, B & C.

Av. Tooth Pitch = .682"; v = 70.8 ft per sec.

c. A large part of the friction being brush friction, this item was subject to an appreciable variation although the greatest care was employed to keep the commutator clean and of uniform polish. All brushes except two, one positive and one negative, were removed from the holders during the tests.

d. The longest gap obtainable was not long enough to eliminate the pole-face loss entirely, hence it was necessary to prolong the curves, (*pole-face loss + core loss* versus *gap*) in order to separate the core loss from the total; but although this prolongation can be made and the core loss determined with a very fair degree of accuracy, the result is the long-gap core loss which is undoubtedly less than that with a very short gap. This error would tend to raise the apparent exponent of q.

The friction error is more or less erratic, but the other three increase with the pole-face loss, the heating error being subtractive and the other two additive. They thus neutralize each other in part, although the heating error is probably less than the other two.

Exponents. By plotting P versus B (for constant speed) on logarithm paper, the exponent of B was determined. By similarly plotting P versus v (for constant B) the exponent of v was determined.

The average exponent of B taken from some forty-five sets of observations is

2.5 for the solid pole shoes
2.4 for the 0.06 in. laminations, and
2.3 for the 0.014 in. laminations.

The fact that the exponent is larger than 2, is probably due, partly to the decrease of permeability at high densities and partly to eddy currents in slot conductors and other abnormal localities. These hardly seem sufficient however to produce as much increase in the exponent as that observed. In the experiments of Wall and Smith both distortional and core-loss errors were practically eliminated and they obtained an exponent for B of 2.1 for solid pole shoes. This should stand as fairly reliable were it not for the predominance of the reluctance pulsation loss in their experiments, and for the fact that only a single set of observations was made.

It is interesting to note that in these experiments the armature core loss itself increased about as the 2.1 power of the flux density; this is doubtless due to the distortional increase.

The average exponent of v was 1.55, a little larger than the theoretical value of equation 6. The apparent excess is probably due to distortional errors.

The variation in λ between the three armatures was not enough to check its exponent, but its effect is quite obvious in the curves of Fig. 14.

An inspection of the computed curve of k^2 in terms of q, (Fig. 8) and the curves of P versus q in Fig. 13, will show that while these curves are not all clearly exponential with respect to q, some of them are very close to that form throughout a considerable part of their length. If it were possible thus to express k^2 as a simple exponential function of q even over a moderate range of that variable, it would be possible to formulate the pole-face loss in a comparatively simple manner.

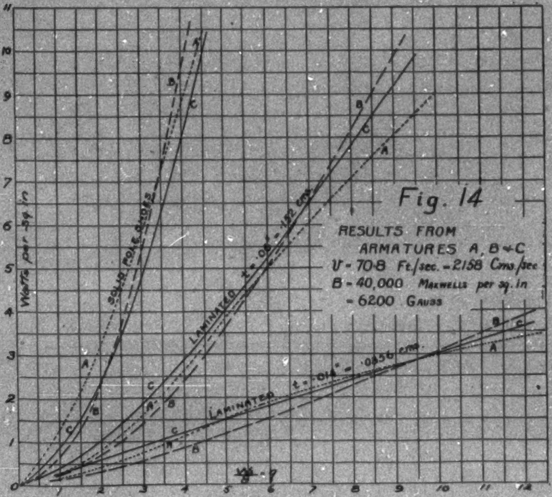
Fig. 14

To this end the theoretical and experimental results were plotted on logarithm paper and the exponents of q averaged.

The lower part of the curve of Fig. 8, covering the working range up to $q = 6$, gave an exponent of 1.8. With armatures B and C the reluctance pulsation loss, increasing with decreasing gap, increased the apparent exponent of q, but the reverse was true of armature A and the average of all three should be fairly reliable; it is, 1.88 for the solid pole shoes, 1.50 for the 0.06 in. laminations and 1.22 for the 0.014 in. laminations.

The lower exponents for the laminated shoes are at least partly due to the *screening* effect within the section of each lamina, tending to force the flux and the eddy currents to the lateral surfaces. This screening is not at all negligible at the high tooth-frequencies employed in the experiments here described, even with the 0.014 in. laminations. The effect of the screening is to decrease the eddy currents by contracting the eddy-current paths and to increase the hysteresis loss by confining the same amount of flux in a reduced cross-section. Both of these effects tend to reduce the exponents of q. Another factor which contributes to a greater extent to these low exponents, is the reluctance pulsation loss which, although small for the long gaps, is large when compared to the small pole-face losses, and thus lifts the lower parts of the P versus q curves by a considerable amount; but the experimental exponents are nevertheless fairly reliable for practical purposes, since they represent fairly average conditions and include the reluctance pulsation losses.

Comparing Fig. 8 with the experimental curves of Fig. 14 it will be observed that the curves for armatures B and C do not show the inflection of Fig. 8, but that the curves for armature A show even an earlier inflection. The reason for this is that the reluctance pulsation loss which in B and C increase with q, in A decreases with q, hiding the inflection in the first case and emphasizing it in the other. As between B and C the former has the larger reluctance-pulsation loss at very short gaps partly because of the larger tooth pitch and partly because of the better ratio between the pole arc and tooth pitch. Thus the B curve crosses the others in each case in the upper range of values.

Formulation of experimental results. Disregarding variations in μ and ρ, the results of the experiments described above may be roughly summed up in the following semi-empirical formulæ. In c.g.s. units, as for equations 1, 6 and 11, they are—

For solid pole shoes:

$$P_s = \frac{2.65}{10^4}\left(\frac{B}{10^3}\right)^{2.5}\left(\frac{v}{10^3}\right)^{1.55} q^{1.88}\sqrt{\lambda} \tag{12}$$

For 0.06 in. laminations:

$$P_{\cdot 06} = \frac{0.985}{10^4}\left(\frac{B}{10^3}\right)^{2.4}\left(\frac{v}{10^3}\right)^{1.55} q^{1.5}\frac{1}{\sqrt{\lambda}} \tag{13}$$

For 0.014 in. laminations:

$$P_{.014} = \frac{0.705}{10^4} \left(\frac{B}{10^3} \right)^{2.3} \left(\frac{v}{10^3} \right)^{1.55} q^{1.22} \frac{1}{\sqrt{\lambda}} \tag{14}$$

In incl. units, the same as for equation 6*a*, these equations become:

For solid pole shoes:

$$P_s'' = \frac{12.9}{10^4} \left(\frac{B}{10^4} \right)^{2.5} \left(\frac{v}{10} \right)^{1.55} q^{1.88} \sqrt{\lambda} \tag{12a}$$

For 0.06 in. laminations:

$$P_{.06}'' = \frac{4.62}{10^4} \left(\frac{B}{10^4} \right)^{2.4} \left(\frac{v}{10} \right)^{1.55} q^{1.5} \frac{1}{\sqrt{\lambda}} \tag{13a}$$

For 0.014 in. laminations:

$$P_{.014}'' = \frac{3.15}{10^4} \left(\frac{B}{10^4} \right)^{2.3} \left(\frac{v}{10} \right)^{1.55} q^{1.22} \frac{1}{\sqrt{\lambda}} \tag{14a}$$

These apply only to the particular conditions of the test as to reluctance pulsation loss, insulation of laminations, μ, ρ, etc., and should be used accordingly. The reluctance pulsation loss was larger in these experiments than with the ordinary chamfered pole tips, but not large enough to give more than a reasonable margin in calculation.

Curves. The most important experimental data from the practical point of view are summarized in the curves of Fig. 13, which show the relation of P (the pole-face watts per square inch) to q (the ratio of slot opening to air gap).

Curves for several densities and for the three different sets of pole shoes are shown. Each curve represents an average for the three armatures and corresponds to a speed of 1246 rev. per min. or a peripheral velocity of 70.8 ft. per sec. = 2160 cm. per sec.

The only apparent reason why the results from the three armatures averaged above should differ, is that the tooth pitches are different; but since λ enters equation 6 as the square root, any moderate difference such as exists between these three armatures does not produce a considerable difference in the pole-face loss. In the present instance this difference was partly masked by the loss due to reluctance pulsation. This will appear from a consideration of Figs. 10, 11 and 12. These figures show that with armature *A* the reluctance pulsations were a maximum with a fairly long gap and a minimum with a very short gap, while with armatures *B* and *C* the reverse is true. Thus the losses in *A* should be relatively large for long gaps (small *q*) and relatively small for short gaps (large *q*.) This is what actually occurs, as shown by Fig. 14, where all the curves correspond to the same mean gap density, (40,000 per sq. in. or 6,200 per sq. cm.), the three groups of curves correspond to the three sets of pole faces, and the three curves of each group to the three armatures.

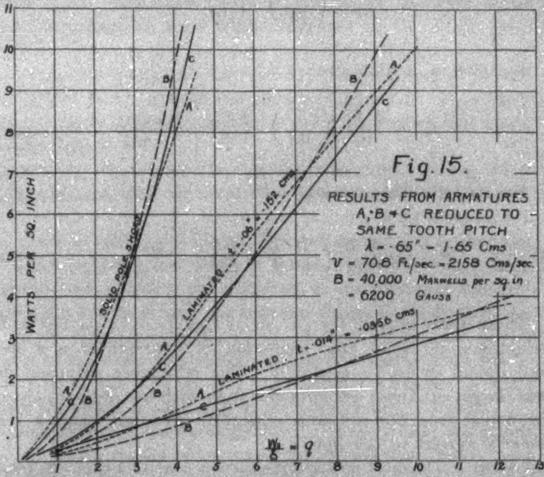

Fig. 15.

RESULTS FROM ARMATURES A, B + C REDUCED TO SAME TOOTH PITCH
$\lambda = .65'' = 1.65$ Cms
$V = 70.8$ Ft./sec. $= 2158$ Cms/sec.
$B = 40{,}000$ Maxwells per sq. in $= 6200$ Gauss

While the curves of the three groups are not all perfectly consistent on this point the general tendency is well marked.

Since armature *A* has the largest λ it should have the largest pole-face loss in the case of the solid pole shoes, and the smallest in the case of laminated pole shoes [see equations (6) and (11).] This is borne out roughly by the curves of Fig. 14, if the reluctance pulsation effect be averaged out.

In Fig. 15 the curves of Fig. 14 are reduced to a common value of λ according to equations 6 and 11. This brings out the reluctance pulsation loss still more plainly.

The averaging of the curves of the three armatures, in Fig. 13, averages the effect of reluctance pulsation to a certain extent, since with armature A this loss is larger with long gaps, whereas with armature B and C it is larger with short gaps. But although this averages two armatures against one, in the one the reluctance pulsation comes with long gaps where the true pole-face loss is very small and the per cent effect is thus relatively large; in fact it probably more than overbalances the other two armatures in the cases of laminated pole shoes, as indicated by the q exponents.

Effect of laminating pole shoes. The theoretical ratio of solid-pole shoe loss to laminated-pole shoe loss, other things being equal is, (see equation 9) $K = a\,2\,t/\lambda$ where a is a constant slightly greater than one, t the thickness of the laminations. and λ the tooth pitch. Take 1.25 as an approximate value of a; then the ratio is, $1.25\,\dfrac{2\,t}{\lambda}$. Take a value of λ equal to the average for the three armatures; it is $\lambda = 0.67$. Then for the two thicknesses of laminations employed $K_{0.014} = 0.052$ and $K_{0.06} = 0.224$. The observed average values of these ratios taken from the average curves of Fig. 13 are $K_{0.014} = 0.11$ and $K_{0.06} = 0.278$. The apparent discrepancy is undoubtedly largely due to the imperfect insulation of the laminations; in fact this was practically demonstrated by the following experiment. After the last regular test with the 0.014 in. laminated pole shoes, the bolts were loosened a little, when it was found that the loss was reduced to 70 per cent of its previous value, which materially closes the gap between the observed and the calculated ratio. This loosening would have been carried further, but owing to the manner of supporting the laminated pole shoes it was not considered advisable. They were still tight enough to hold the shoes together firmly when supported by two half-inch screws tapped directly into the back side of the laminations.

Another factor which contributes considerably to this discrepancy is the reluctance-pulsation loss which adds a much larger percentage effect to the laminated-shoe losses than to those of the solid shoes.

A probable change in μ and ρ from the solid to the laminated shoes may also account for a part of the discrepancy.

It is thus reasonable to assume that with perfect insulation between the laminæ and with the reluctance-pulsation loss eliminated, the calculated losses would check very closely with the observed losses. The greater discrepancy in the case of the thin laminations is due to the much greater number of partly insulating surfaces, and to the greater percentage effect of the reluctance pulsation loss.

Additional pole-face losses. There are other losses which sometimes add to those here measured for the laminated pole shoes; they are chiefly due to transverse rivets and to the large heads of flat-head screws sometimes used to hold on the laminated shoes.

Except in the case of reluctance pulsations, the rivets do not contribute much to the total loss, owing to the very slight penetration of the tooth flux waves, (about 0.03 in. or 0.04 in.).

The large screw heads do, however, make a considerable addition; for example, the pole shoes which originally accompanied the machine under test had screw heads which occupied 7 per cent of the pole-face area. These pole shoes were of 0.06 in. laminations, so that taking the experimental ratio above, the screw heads would add about 30 per cent to the pole-face loss. With 0.014 in. laminations well insulated the same screw heads would add about 100 per cent to the loss.

Minimum air-gap. Owing to the numerous variables involved, it is impossible to make any general rule as to the smallest allowable air-gap or the largest allowable value of q, but a careful study of the curves of Fig. 13 together with equations 6 and 11 should make possible a reasonably intelligent decision for any given case.

Comparison of theoretical with observed results. Although the numerical coefficients and exponents in the wholly theoretical equations cannot be expected to give satisfactory practical results in a problem involving so many complex relations, it may be interesting nevertheless to see how closely these results compare to those observed. The observed results for comparison are obtained by averaging the three curves in each set of Fig. 15. In making the theoretical computations k^2 is taken from the curve of Fig. 8; μ is taken as 2000 and ρ as 1.5×10^3 in absolute electromagnetic units; a in equation 11 is taken as 1.25; $\lambda = 0.682$ in. $= 1.73$ cm. $v = 70.8$ ft. per sec. $= 2160$ cm. per sec.

In Fig. 16 are plotted the three averaged observed curves, one for each set of pole shoes and all for the same density, 40,000 per square inch. The light line curves were computed from equations 6 and 11 and the data assumed above, for the same conditions.

It is thus evident that when the imperfect insulation of the laminations and the reluctance pulsation loss are taken into account, and when it is remembered that μ and ρ are not at all accurately known, the theoretical results compare very well with those observed.

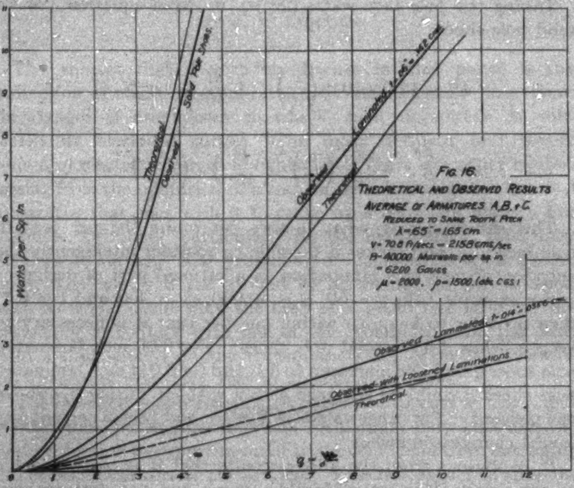

FIG. 16.
THEORETICAL AND OBSERVED RESULTS
AVERAGE OF ARMATURES A, B, & C.
REDUCED TO SAME TOOTH PITCH
$\lambda = .65'' = 1.65$ cm
$v = 70.8$ ft/secs $= 2158$ cms/sec
$B = 40000$ Maxwells per sq. in.
$= 6200$ Gauss
$\mu = 2000$, $\rho = 1500$. (abs. C.G.S.)

Distortion due to armature reaction. All the results thus far obtained apply only to no-load conditions, but the effect of armature distortion is easily taken into account. Given the dimensions and data of the machine, lay out the full-load flux distribution and compute the *form-factor* (ratio of root mean power to average value) of this curve. Multiply the no-load loss by this *form-factor*.

Design considerations. It will be interesting now to compare the watts lost per unit of pole-face area with the useful watts developed in the equivalent armature area, as their ratio will give the per cent pole-face loss.

Let $\triangle$ = the peripheral armature current (ampere conductors per inch of periphery),

v = peripheral velocity of armature in ft. per sec.

B = mean pole-face density maxwells per sq. inch.

Then the useful watts developed per sq. in. of pole face is

$$P_0'' = 12\,v\,\triangle\,B\,10^{-8}$$

Taking the pole face watts per sq. in. from equation 12*a* for solid pole shoes:

$$P'' = 12.9 \times 10^{-4} \left(\frac{v}{10}\right)^{1.55} \left(\frac{B}{10^4}\right)^{2.5} q^{1.88} \sqrt{\lambda}$$

$$q_{pf} = \frac{P''}{P_0''} = \frac{1.07}{10^3} \left(\frac{v}{10}\right)^{.55} \left(\frac{B}{10^4}\right)^{1.5} \left(\frac{\triangle}{100}\right)^{-1} q^{1.88} \sqrt{\lambda}$$

This shows clearly what factors determine the per cent of pole-face loss, and makes it possible to consider intelligently the question of pole-face lamination as a rational part of design.

For example, take $v = 50$, $B = 40{,}000$, $\triangle = 400$, and $\lambda = 0.7''$ then in order to keep q_{pf} within one per cent it is necessary to keep q below 1.6 for solid pole shoes. For 0.06 inch laminated pole shoes q could be increased to 3.1, and for 0.014 inch laminated pole shoes q could be as large as 5.9 without raising q_{pf} above one per cent. For other values of B, v, $\triangle$, and λ these percentages would change somewhat.

It is obvious from the above results that it is quite possible to get values of q_{pf} considerably above one per cent without exceeding ordinary proportions.

Although there are other considerations than that of pole face loss which frequently control the choice of the air gap and of the pole shoe type, it is hoped that the experimental results and analysis above presented may help toward a more rational consideration of these questions.

A paper presented at a joint meeting of the Seattle Section of the American Institute of Electrical Engineers and the Northwest Electric Light and Power Association, Seattle, Wash., September 8, 1909.

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PROTECTION OF ELECTRICAL EQUIPMENT

BY P. M. LINCOLN

The subject that I wish to discuss in this paper is the protection of electrical apparatus and transmission lines from the danger of breakdown to which such apparatus is subjected by electrical surges. The most frequent and severe source of electrical surges is lightning. There are other causes, arising from the operation of a transmission line and the electrical apparatus that goes with it to make up a complete plant. For instance, switching, particularly on the high-tension side, may give rise to surges. Also grounding of high-tension transmission lines, particularly if the ground be an arcing one; for instance, such as would occur were the limb of a green tree to come occasionally in contact with one of the conductors of the line. Also a short-circuit on the transmission line or on other electrical apparatus may give rise to an electrical surge.

The question which I wish particularly to discuss in this paper is, therefore, the manner in which such surges may arise and the best protection to supply in order to prevent them from damaging either the apparatus or the service. I do not expect in this discussion to bring out anything new. The most that I could possibly expect is to bring a new viewpoint to some who are interested in long-distance power transmission and the protection of transmission circuits from damage and interruption.

What is meant by the term "surge"? This is a fair question and should have a straightforward answer. If this question were to be asked of a Steinmetz, he would fill pages with differential equations and $\int$ signs of integration and finally give an answer (as he has already done) in the form of a mathematical formula.

Such an answer, although it tells the story, is unfortunately useless to the average long-distance transmission line operator, since it requires the mind of a trained mathematician to interpret such an answer as well as to make it.

For my own part I have found that a proper conception of the phenomenon of electrical surges can be much better conveyed to the mind by using an analogy. The use of a proper analogy conveys a concrete idea rather than an abstract one, and the mind can much more readily grasp the idea in that shape than when it merely consists of abstract ideas which must always be associated with such electrical terms as volts, ohms, henrys, microfarads, etc. Any analogy must be used carefully, since in many points of comparison it is apt to fail. If improperly used, it may lead to conclusions entirely wrong; but if properly applied it will lead the average mind to a much clearer conception of what is going on than can be obtained by any consideration of abstract quantities.

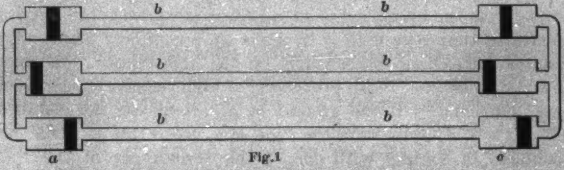

Fig.1

In many respects the following hydraulic analogy is similar to the electric circuit, and I trust that its description will be of assistance to some in gaining an idea of an electric surge. Suppose we replace a three-phase alternating-current generator, transmission line, and receiving apparatus with a hydraulic arrangement as shown in Fig. 1. In this Fig., *a* is the piston pump with the three pistons 120 degrees apart. *c* is a duplicate of pump *a*, whereby the work done by *a* is transferred to *c*; *b b b* are pipes connecting *a* with *c*. The likeness to an alternating-current power transmission system is accentuated in our analogy by the fact that the water or other liquid in the system simply oscillates through the pipes *b b b* from generator pump *a* to motor pump *c*. In order to endow this hydraulic system with the functions of an electric circuit we will have to imagine that the walls of pipes *b b b* are perfectly flexible; for instance, made of pure india rubber. This introduces into our hydraulic system the analogy of static capacity in the electric system. If we imagine that water is to be used in the hydraulic analogy, the weight or inertia of this water introduces into the hydraulic system the equivalent of inductance or reactance in the electric system. Since the water in passing back and forth will have certain losses due to friction against the walls of the pipe and pumps, the idea of ohmic resistance of the electric circuit is transferred to the hydraulic analogy.

If we wish to imagine the effect of increasing static capacity, we may do so in our hydraulic analogy by imagining the walls of the pipe to become more flexible; for instance, made of thinner walls of rubber. For a transmission line without capacity we would have to substitute a hydraulic system with perfectly rigid and inflexible pipes. Increasing inductance or reactance may be represented in our analogy by increasing the weight and therefore the inertia of the liquid pumped; for instance, by substituting mercury for water. Increasing electric resistance may be represented by smaller, rougher, or longer pipes, thus increasing the frictional resistance. It is further necessary to assume that the volume of the pump cylinders is large compared with the volume of the pipes connecting the two pumps; and to gain a proper idea we would have to imagine further that the speed of the pumps is slow, say one stroke per minute or so.

Now if we can keep our imaginations under proper control and can carry this hydraulic analogy in our minds we are prepared to investigate the nature of an electric surge by means of this analogy. Suppose we suddenly inject into one of the flexible pipes *b b b* at some point between pumps *a* and *c*, an amount of liquid which will instantly swell the pipe at that point to some three or four times its normal diameter for a length of some eight or ten diameters. This would be analogous in the electric system to the effect of lightning. A cloud discharges in the neighborhood of a high-tension transmission line. The area of the transmission line which has been covered by the cloud is relatively small. The discharge of that cloud releases in the transmission line a certain amount of static electricity in addition to the normal amount of current present due to the action of the generators and receiving apparatus. What happens next? It is much easier for the imagination to follow this in the analogy than in the actual transmission line. If the pipe is not strong enough the wall breaks; that is, an insulator punctures or "slops over," and the accumulation of water, [electricity] in part at least, escapes. If the walls of the pipe are strong enough to stand the strain; that is, if the insulators do not break down, a wave or surge begins to be propagated in both directions. The distended walls of the pipe bring their elastic force to bear upon the enclosed liquid and the accumulated "lump" of water begins to de dissipated in both directions. Inertia of the liquid together with the pressure on it from the elastic walls will cause it to assume successive forms which are probably very much like those shown in Fig. 2. The accumulation of liquid will become longer and thinner, and it finally divides into two separate lumps as it travels from the point of disturbance in both directions. At the point of disturbance the tendency to break the walls is a maximum, and this tendency becomes less and less as the wave or surge proceeds from the point of disturbance. However, should the surge encounter a weak place in the walls, a break may occur in some place comparatively remote from the point of disturbance.

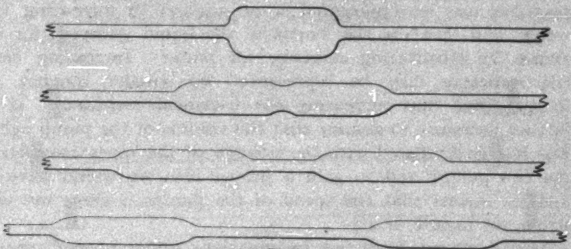

Fig. 2

Now, what happens when this wave or surge reaches the electrical apparatus at the ends of the line? For the purpose of considering this question, we should have to replace our pumps with something that would behave like a transformer or generator in an electric system. Now generator and transformer windings have two important differences from an equal length of transmission line, in that both the capacity and inductance per unit length are largely increased. In our hydraulic analogy the increase in capacity per unit length may be represented by imagining a much thinner walled pipe for the generator. The increase in inductance per unit length may be represented in the analogy by an increase in the specific gravity of the liquid, say by substituting mercury for water. I have endeavored to give a graphic representation of these modifications in Fig. 3.

b_1 is the transmission line with relatively heavy walls, although still flexible, and a light liquid contained therein, say water.

b_2 is the generator which has relatively thin but still perfectly elastic walls containing a heavy liquid, say mercury.

When the wave or surge that has been started out on the line b_1 reaches the point p; that is, the terminal of the generator or transformer, it is obvious that the following things will occur:

1. A part of the energy of the incoming wave will be reflected and will therefore travel back through the line b_1 from the point p.

2. The remainder will begin to travel through part b_2, the generator or transformer; but the speed of its propagation will be very much reduced, because the liquid being set in motion is very much heavier and also because the forces acting upon it through the elastic retaining walls are much smaller.

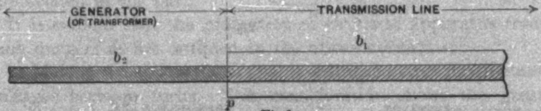

Fig.3

3. The steepness of the wave-front during its propagation through b_2 will be very much increased over that obtaining in b_1, on account of the action of the same forces as noted in the above paragraph.

I have allowed my own imagination rather free play, and give in Fig. 4, 5, 6 and 7 my idea of how the wave will modify itself when being propagated from medium b_1 to medium b_2. Probably the most noteworthy modifications during this transfer of the disturbance from b_1 to b_2 is the abrupt increase in the steepness of the wave-front. For instance, consider the points p_1 and p_2 in Fig. 5. At p_1 there is a tendency to burst the pipe; that is, to break down the insulation to ground; but there is also a heavy stress tending to break through from point p_1 to point p_2. Suppose that the portion b_2 of our pipe, instead of being straight as indicated in the diagram were to be coiled upon itself, and that one complete coil took place in the distance from p_1 to p_2, then there would be a tendency for the liquid at point p_1 to break through the walls of the pipe into the neighboring coil at p_2. This is exactly what occurs in the electric system. An incoming surge, in penetrating the turns of electrical apparatus, causes an excessive voltage strain between adjacent turns. The momentary breakdown or snapping across of this surge from one turn to the next will do no particular damage unless such breakdown is followed by the dynamo current and an arc is thereby established. If this later event occurs then the break does tre-

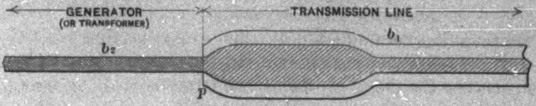
GENERATOR
(OR TRANSFORMER)
TRANSMISSION LINE
b_2
b_1
p

Fig.4

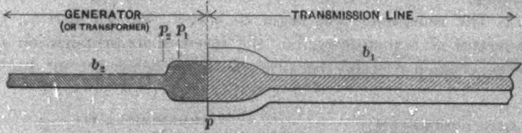
GENERATOR
(OR TRANSFORMER)
p_2
p_1
TRANSMISSION LINE
b_2
b_1
p

Fig.5

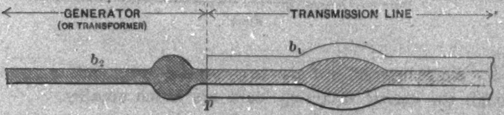
GENERATOR
(OR TRANSFORMER)
TRANSMISSION LINE
b_2
b_1
p

Fig.6

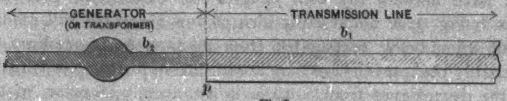
GENERATOR
(OR TRANSFORMER)
TRANSMISSION LINE
b_2
b_1
p

Fig.7

mendous damage. In my opinion, practically all the failures in generators, transformers, etc. which can be traced directly to lightning or other surges are due to a breakdown between turns rather than to a break in the insulation from conductor to the ground. There is, of course, due to the normal operation of the apparatus, an insulation strain from conductor to ground and also one between adjacent turns. A surge momentarily increases both of these strains. The strain to ground may be thereby increased 20 per cent, 50 per cent, or perhaps 100 per cent, or even somewhat more; the strain between turns may thereby be increased twenty times, fifty times, one hundred times or even more. A surge, therefore, throws a much larger increase on the insulation between turns than it does on the insulation to ground. From certain observations that I have made, it is my opinion that the momentary strains between turns, particularly near the terminals of the apparatus, may approximate a considerable percentage of the terminal pressure. This is a danger in electrical apparatus which has not been sufficiently appreciated in the past.

It is evident that the protection of electrical apparatus from such dangers as are outlined in the above consists in:

1. Making the apparatus so that it will stand large momentary voltages between turns. This consideration shows the great advantage possessed by transformers, particularly oil-insulated, over generators. It is possible to insulate transformers between turns to a much higher degree than any generator can be, particularly where oil is used.

2. Limiting by use of proper lightning arresters the size of the wave or surge that may enter the electrical apparatus. Reverting to the hydraulic analogy, if we should provide a hydraulic relief valve at the point *p*, Fig. 5, it would have the effect of removing at least a part of the excess liquid at the instant the strong pressure on the walls occurs. If this relief valve were to be set so that it operates at a pressure of, say, only 20 to 30 per cent above that caused by the pumps while in normal operation, then this relief valve would not affect the normal operation and would also limit a surge or wave entering part b_2 to an amount which could not exceed 20 or 30 per cent above normal pressure or voltage. This indicates the function of the ideal lightning arrester. It prevents any electrical surge which has a value of 20 to 30 per cent greater than normal voltage from entering the electrical apparatus. This is the utmost that any lightning

arrester can do. The electrical apparatus itself must be so designed that it will take care of an entering surge which is not more than 20 or 30 per cent above line voltage.

Reverting again to the hydraulic analogy, suppose our relief valve has a relatively long discharge pipe, say one-one-hundredth the area of the incoming pipe *b* in Fig. 1. The time during which the excess pressure exists at *p*, Fig. 5, is relatively small. Such a pipe attached to the relief valve would be utterly unable to discharge a sufficient amount of the liquid to relieve the pressure. As a consequence, the size of the surge entering part b_2 would be but little reduced by such a relief valve. This is analogous to what occurs with a lightning arrester having a large ohmic resistance in series with it for the purpose of preventing the dynamo current from following. This indicates in general why this type of arrester is inferior to the electrolytic. The electrolytic type of arrester, once broken down, has almost a zero resistance to ground and therefore allows the maximum possible reduction of the surge before it enters the electrical apparatus.

Another method of protection that has shown itself of considerable value both in theory and practice (as a protection from lightning) is the overhead grounded guard-wire. The theory of this kind of protection is as follows:

Any conductor that is entirely enclosed or surrounded by another conductor cannot have induced thereon a static charge which originates from any action going on outside the surrounding conductor. For instance, a lead-covered electric cable cannot be directly subjected to lightning disturbances because of the protective action of the surrounding lead sheathing. The overhead ground-wire acts to a certain extent in the same manner. Although it does not entirely surround or enclose the high-tension wires which it protects, it does so partly and to the extent that it does enclose or surround the high-tension wires it provides the same protection as does the lead sheath to the underground cable. In the electric transmission circuit the voltage of the charge which would otherwise be induced upon the transmission line is kept down by the presence of the guard wires.

Still another method of protecting high-tension transmission lines is to ground the neutral of the lines. This grounding may be done either by connecting it solidly to the ground or by putting in a greater or less resistance between the neutral point and the ground. To just what extent this grounding of the neutral, either completely or partly, is of value is a moot question among engineers. As I see it, the question of grounded neutral versus ungrounded may be considered from two viewpoints: first, from the viewpoint of protection of the apparatus or equipment; secondly, from that of the protection of the service.

First: protection to apparatus. The advantage in a solidly grounded neutral, so far as protection to apparatus is concerned, is that the normal voltage to ground can under no conditions rise to more than about 58 per cent of the normal voltage between conductors. This advantage is, of course, of the utmost importance when considering insulation strengths to ground of the various apparatus involved.

On the other hand, the disadvantage of a solidly grounded neutral is that every ground which occurs develops immediately into a short-circuit, and these short-circuits in turn cause severe mechanical stresses to be set up in the windings of the transformers and the generating apparatus.

With a grounded neutral, therefore, it is reasonable to expect that the windings of the transformers and generators will be subjected to much more frequent shocks than without such a ground. Also owing to the fact that every ground immediately becomes a short-circuit, and that at the points of short-circuit the arc will cause considerable destruction, the system with the solidly grounded neutral will be subject to more frequent destructive arcs both on the line and in the apparatus where there is probability of such arcs developing.

It is my opinion that so far as protection to apparatus is concerned, the advantages of grounding the neutral very much outweigh the disadvantages; and if protection to apparatus alone were to be considered, I would have no hesitation in recommending a solidly grounded neutral.

Secondly, protection to the service. As mentioned above, the disadvantage of a solidly grounded neutral is that every ground develops immediately into a short-circuit. With a voltage such as is always used in high-tension transmission, (say 44,000 and above) there will always be a sufficient voltage at the point of arc to cause that arc to continue until the power to that particular section of line is cut off. This fact almost invariably will cause an interruption of power whenever a ground occurs at any point on the transmission system.

This would not be so materially a disadvantage were it not for the fact that experience has again and again demonstrated that lightning storms will very often cause insulators on the line to arc across or puncture. With the neutral solidly connected to ground, each one of these punctures and flash-overs means an interruption of service. If the line were not solidly grounded, it is probable that many of these flash-overs would not interrupt the service, since a flash-over involving only one conductor might simply mean that the other two conductors on the transmission line would momentarily rise to a potential nearly double normal while the arc at the defective insulator, as well as the voltage to maintain the arc, would disappear.

In view of the difficulties which the line is apt to encounter with a solidly grounded neutral, many engineers prefer to ground through a resistance instead of connecting the neutral solidly to ground. In order to be of use, the resistance between the neutral and ground must be relatively high, and further it must be able to carry a considerable current for at least a short period of time. In other words, it must be capable of dissipating a very considerable amount of energy for a short period. A satisfactory type of resistance for this grounding service is difficult to obtain. Cement columns have been used, but these are unsatisfactory owing to the extreme variability of their resistance. Also if the current through them is maintained for an appreciable time, the heat developed is apt to crack or even to burst them. After studying the question from various angles, I have come to the opinion that a metallic form of resistance is the proper one to use for this purpose. The main disadvantage of this form is its cost, but its advantages are sufficiently great to overcome this disadvantage.

To recapitulate briefly: the protection against surges of electrical equipments, including both the apparatus and transmission lines, may be furthered by adopting some or all of the following methods.

1. *The overhead guard-wire.* This has the ability of keeping down the quantity of electricity which a given lightning discharge is capable of superposing upon a transmission line. In practice it has shown itself to be a valuable device in many instances of high-tension transmission.

2. *The use of efficient lightning arresters is essential.* They should be of a type which will allow a free discharge of static electricity from the transmission line whenever the voltage of the charge exceeds normal by a certain predeterminable amount.

With a proper equipment of such lightning arresters, the size of the surge which may enter electrical apparatus is limited.

3. *The grounded neutral.* Grounding solidly prevents the potential of a neutral point of a transmission line from departing from ground potential. This in turn will prevent the normal operation of this line from causing more than about 58 per cent of line voltage to appear between any conductor and ground. Grounding through a resistance has the same effect, to an extent depending upon the amount of resistance used.

4. *Insulation between turns.* The analysis in the preceding discussion shows that it is highly essential to insulate electrical apparatus between turns so that it will stand a momentary potential which is many times that normally put upon the insulation. The consideration of this point shows at once the enormous advantage of using transformers upon a transmission line in distinction to connecting generators direct. The amount of insulation that can be used between turns in a generator is limited by the necessity of placing the winding in relatively small slots. In a transformer this consideration does not operate to nearly so great a degree, owing to the fact that the space occupied by the windings is, so to speak, in one piece instead of being divided into a large multiplicity of small slots. Also the presence of oil in the case of the transformer gives it an advantage which the generator cannot have under any conditions.

A paper presented at the 239th meeting of the American Institute of Electrical Engineers, New York, October 8, 1909.

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TELEGRAPH AND TELEPHONE SYSTEMS AS AFFECTED BY ALTERNATING-CURRENT LINES

BY JOHN B. TAYLOR

General. In the early days of the electrical industry the telegraph practically had the field to itself. The telephone and electric light were introduced at about the same time, and later on the alternating-current systems gradually came into general use for lighting, general power, and railway purposes. At the outset, the telegraph systems made use of earth return and continue to do so at the present day. The telephone systems started out to use an earth return, but soon found that satisfactory service, except in isolated cases, could be obtained only with metallic circuits. The power systems (this term includes alternating-current systems whether used for lighting, for power or for railway purposes) have until recently almost invariably used metallic circuits, which, when properly installed and under normal conditions, cause little interference to telegraph and telephone lines. Abnormal conditions, however, such as grounds, open circuits, and the like, upset the normal balance, giving strong external fields, both electrostatic and electromagnetic, which are likely to make trouble for sensitive systems in the immediate neighborhood. Recently the single-phase railway system has come into prominence. With this system the conditions are continuously very similar to those conditions which exist occasionally but of short duration on the power systems.

The great increase in the transmission industry means that power circuits are continually becoming longer, voltages higher, and the amount of energy transmitted greater, with more or less corresponding increase in disturbance to the weaker brothers. Steam railroads have in many cases presented the most natural and logical right of way for pole lines, with the result that power wires and signaling lines are likely to be in proximity.

The telegraph, telephone, and power systems, while rendering different classes of service, are all essential to present methods of living and carrying on business. The purpose of this paper is to give a general statement of power transmission and telegraph and telephone conditions as they exist, with special reference to combinations which may make trouble if simultaneous operation is attempted in too close proximity.

It should be borne in mind that induction between circuits is a mutual affair, the principal distinction being that a high-voltage transmission line conveying perhaps 1000 to 5000 kw. is not disturbed by, nor even able to detect, a few extra volts derived by induction from a telegraph line on the other side of the highway. The converse of this proposition is by no means true, and this points to the desirability of power transmission systems doing everything possible to keep the stresses and strains in the ether within the boundaries of their own right-of-way, and the equal importance of telegraph and telephone apparatus and lines being so constructed and maintained that they will be, as far as possible, independent of stresses and strains which may be unavoidably introduced into the portion of the ether which they occupy. An adequate consideration and solution of the problem necessarily involves an intimate study of the characteristics and sensibilities of telephone and telegraph instruments as well as a calculation of disturbing electromotive forces and currents induced in their circuits with values depending upon all the various features of construction and operation of the power lines.

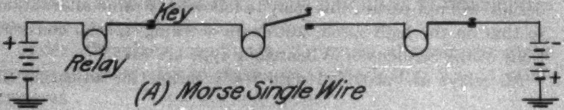
Telegraph systems. The telegraph circuit, with few exceptions, is made up of a single wire and earth return. The typical Morse system is represented in Fig. 1, Diagram A, showing relays, keys, and a battery at each end of the line. Relays are usually of 150 ohms resistance, and the normal working current is in the neighborhood of 40 milliamperes, although many circuits having a large number of intermediate stations make use of 37.5 or 35-ohm relays and on these circuits the current will probably average nearer to 50 than to 40 milliamperes.

Diagram B shows a typical arrangement of duplex circuit, in which case relays are polarized with differential windings. This arrangement does not permit the insertion of intermediate stations.

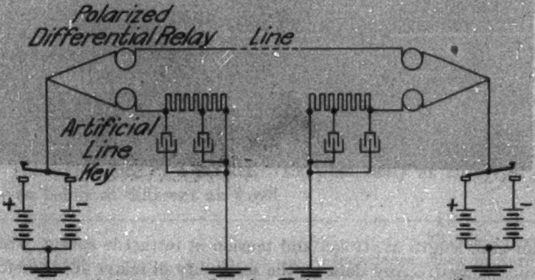
A quadruplex system is an extension of the duplex, by placing in circuit a second differential relay so adjusted as to respond only to currents greater than those required for operating the polar relay, and means for changing the strength of current.

The duplex system ordinarily uses current of 12 to 15 milliamperes and the quadruplex uses three to four times this current, say 35 to 50 milliamperes, for actuating the neutral relay.

As far as the main line circuit is concerned, these two systems include nearly all the various types of high-speed, automatic printing telegraphs, etc., the main difference being in the types of relay and local apparatus controlled by them, as well as the duration and polarity of signals and the code used. For example, the Rowland system recently described in an Institute paper,* is essentially a duplex system, the octoplex capacity being obtained by assigning the line for short intervals of time to one of the four operators at each end in succession.



(A) Morse Single Wire



(B) Typical Duplex Telegraph Circuit

FIG. 1

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* The Rowland Telegraphic System, by Louis M. Potts, PROCEEDINGS, A. I. E. E., April 1907, p. 409.

The frequency of the currents for hand transmission probably averages in the neighborhood of 8 to 10 cycles, although this is a crude way of putting the matter, as signals are short and long, interspersed with spaces. The Wheatstone automatic system, when working up to an extreme speed of 600 words per minute, gives alternate pulses in the line corresponding roughly to 240 cycles per second. The Rowland system as described uses approximately 100 cycles for octoplex working and 50 cycles for quadruplex working. The inertia of the armature of the standard 150-ohm relay, and other features of its magnetic design, will not permit this relay to follow very rapid alternations so that on the high-speed, automatic-working, special constructions of the Siemens or Wheatstone type are used.

All relays are provided with ready means for adjusting the air-gap, length of stroke, and tension of retractile spring, where such is used. Any data on the sensibility of relays are therefore greatly dependent on these various adjustments. Furthermore, adjustments are continually being made by the operators to compensate for variable leakage of the line, due to weather conditions, and also to compensate for variable current and lag, depending on the relative positions on the line of sending and receiving operators. It is therefore impossible to make a general statement that a certain number of milliamperes added to or subtracted from the normal direct current, due to inductive influence, will disturb or completely upset the working, and that a lesser superimposed current will not be felt.

FIG. 2

Experienced operators recognize their friends by the way the instrument "talks," quite as distinctly as those who are not operators recognize handwriting or the sound of the voice. This is stated to bring out the point that disturbances on the line which do not actually upset the working may make considerable difference in the comfort or state of mind in which the operator does his work.

In order to give some idea of the characteristics of the standard 150-ohm relay, tests have been made under the following adjustments:

Magnetic air-gap 0.07 in.

Length of stroke at contacts 0.015 in.

Spring tension so that relay would pick up at 40 milliamperes direct current, and let go at 30 milliamperes.

Under the above conditions, 25 cycles alternating-current current to cause relay to chatter on the back stop, was 31 milliamperes.

Current to cause relay to pull up to front stop sufficient to start chattering in local sounder, was 62 milliamperes.

With 40 milliamperes direct current in relay—superimposed 25 cycle current to cause relay to break contact on the front stop, 20 milliamperes.

As stated above, different adjustment of gap, length of stroke, and spring tension would give quite a different set of current values. Oscillograms, Fig. 2 shows the current in main line relay and in local sounder with 25-cycle alternating current superimposed on line.

The impedance of a standard 150-ohm relay at 25 cycles is given below at different air-gaps.

Air Gap	Impedance	25-cycle current when measuring impedance
0.12 in	465 ohms	89 milliamperes
0.11 "	474 "	88 "
0.10 "	488 "	86 "
0.08 "	515 "	82 "
0.06 "	555 "	77 "
0.05 "	580 "	74 "
0.04 "	650 "	67 "
0.03 "	725 "	61 "

Special apparatus on telegraph lines. Where a telegraph disturbance is slight, improvement may be effected by one or more of the following expedients:

Increasing impedance of line.

Increasing working current.

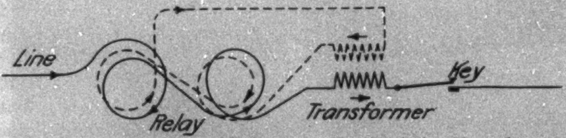
Shunting apparatus with condensers or non-inductive resistance.

Placing short-circuited secondary winding on relay.

Placing neutralizing winding on relay.

Using back contact of relay with reversing sounder.

By placing additional resistance and reactance in the telegraph circuit, the superimposed alternating currents will be reduced in proportion to the increase of impedance. At the same time the battery should be increased to maintain the normal direct current, at its usual value. By working the line at a higher value of direct current, the percentage increase and decrease due to induced alternating currents will be less, with consequent reduction in the disturbance of the relay. Shunting the relay with a condenser or a non-inductive resistance diverts a portion of the alternating current from the inductive winding of the relay. While a condenser bridging a single relay will help this particular instrument, it will not help the line as a whole. By placing the relay winding over a thick copper tube or on a copper spool, alternating currents will be induced in the copper tube which will tend to oppose the effect of the alternating current in the winding.



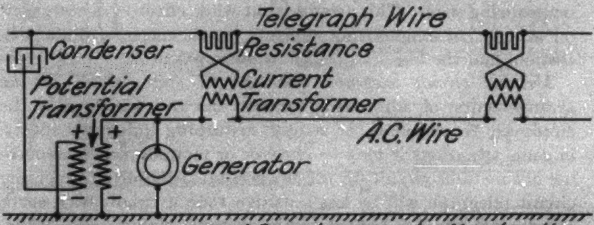
Differentially Wound Relay with Neutralizing Transformer

FIG. 3

In the second winding of a differential relay, currents in opposite direction to the alternating currents in the main winding may be introduced by means of a small transformer connected as shown in Fig. 3.

Since the signaling currents in a telegraph line are of the nature of alternating currents, it can be seen that any of the above choking, shunting, absorbing, or neutralizing devices will tend to make the action of the relays sluggish; and as soon as the frequency of the signaling currents equals or exceeds that of the induced currents, these devices will become a hindrance rather than a help.

When the telegraph line is open, the relays are against their back stops; and with the line open, there would be no current, either direct or alternating, except for leakage and capacity effects. The air-gap is also at its greatest, so that the relay is less likely to be disturbed while on the back contact than when on the forward contact. By taking the local circuit from a back contact on the relay, and adding a reversing sounder the inductive disturbance may be less noticeable. This is a combination known as a "bug-trap," having been devised by Mr. Edison in the early days of the quadruplex. It is also possible to accomplish a similar result by using a flexible or spring contact on the relay. Such a contact allows a slight vibration of the armature without causing the local circuit to open.



Transformers and Condensers to Neutralize Electro-magnetic and Electro-static Induction

FIG. 4

The devices considered just above are only palliative remedies. When the amount of power transmitted, length of line, or small separation of the two circuits is such as to make the disturbance severe, definite neutralizing conditions must be introduced.

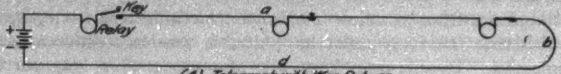
If we can introduce into a telegraph circuit voltages equal and opposite to those derived by electromagnetic induction, and at the same time supply to the line the charge demanded by electrostatic induction, we shall succeed in neutralizing the inductive effects. Fig. 4 shows one way in which this idea may be worked out. Current transformers connected in a disturbing wire introduce into the telegraph line a voltage proportional to the current in the transformer. Since on a railway the position of the load is shifting, it would be necessary to divide the line into sections, with a transformer for each. The shorter the sections, the more exact the neutralization. Electrostatic induction is neutralized by using condensers in connection with potential transformers as indicated. The proper charge can be obtained by varying the capacity of the condensers or the voltage applied to them.

Instead of using current derived directly from the disturbing wire for the purpose of neutralizing, this neutralizing current may be derived from a special neutralizing wire placed close to the disturbed telegraph wires. Since the neutralizing wire has practically the same exposure as the telegraph wire, the same voltage will be induced in each, and a suitable 1:1 transformer makes proper change of polarity so that voltage induced directly in the telegraph wire is annuled by that induced in the neutralizing wire. This arrangement while effective is not exact, on account of magnetizing currents, earth currents, phase distortion, and the like.

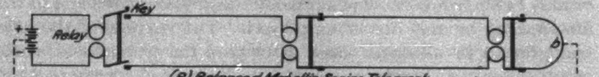
Metallic circuit telegraph systems. In spite of all of the arrangements of alternating-current circuits which may be employed to eliminate or reduce disturbing inductive effects, in some situations it may be cheaper or more desirable to make use of a metallic circuit for the telegraph. Any form of metallic circuit telegraph will be less sensitive than a circuit with earth return, but the full benefit of the metallic circuit is to be derived only when following the "balancing" principles to be stated more in detail when discussing the telephone.

The metallic telegraph may be operated on either the series or multiple connection, and either of these connections properly installed will be perfectly balanced. The same might be said of the telephone system, although as far as the writer is aware a balanced metallic series telephone system has never been used.

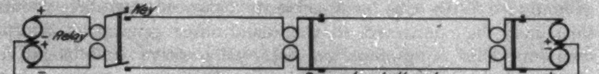
Inductively considered, corresponding points on the two wires of a telephone or metallic circuit telegraph system are at the same potential. Slight differences in potential due to the difference of field strength in the 10 or 12 in. separating two wires in practice is made insignificant by frequent transpositions, and small charging currents must flow back and forth from one section to another, owing to the slight difference of potential between the two wires. Pieces of apparatus such as telephone receivers, bells, or telegraph relays, "bridged" between the two wires are, therefore, free from inductive currents. If the apparatus be connected in series, in order to preserve the balance it must be differentially wound, an equal winding being cut into each side of the line. With such an arrangement, on account of the differential action of the two windings, induced currents or electrostatic charges flowing from one section of the line to another section will not affect the instrument.


Key
Relay
a
b
c
d
+
-

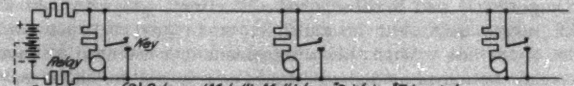
(A) Telegraph with Wire Return



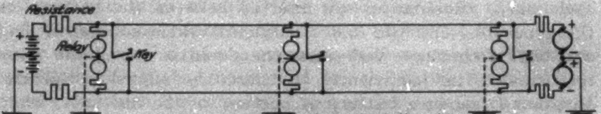
(B) Balanced Metallic Series Telegraph



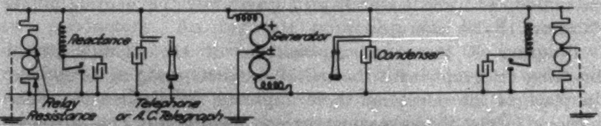
(C) Balanced Series Generators both ends Neutral grounded


Key
Relay
Resistance
+
-

(D) Balanced Metallic Multiple or "Bridging" Telegraph


Resistance
Relay
Key
+
-

(E) Balanced Multiple Generator both ends Neutral grounded at several points


Reactance
Generator
Condenser
Relay
Resistance
Telephone
or A.C. Telegraph
+
-

(F) Bridging Connections for Simultaneous Telegraph and Telephone or Duplex Telegraph D.C. and A.C. with Intermediate Stations.

FIG. 5

Fig. 5 shows several connections which may be used for the metallic circuit telegraph. Diagram A shows an ordinary series telegraph system with wire return in place of earth return. If the conditions are such that electrostatic effects can be neglected, this arrangement, though not balanced, will be satisfactory.

Diagrams B and C show a balanced metallic series telegraph. In this case the relay must have double windings differentially connected. Double-pole keys are also essential. Diagram B shows a battery, which may be grounded at the neutral point or may be ungrounded; and similarly the ground at the end of the line, *b*, may or may not be employed. The purpose of the neutral ground in all these cases is to keep the system as a whole at approximately earth potential. In Diagram C, generators are shown at each end of the line, the neutral connection being grounded. With this arrangement, balanced metallic circuit lines may be connected to the usual office generating equipment, as this equipment consists of positive and negative machines at approximately the same voltage, with one terminal grounded.

Diagrams D and E show a metallic circuit telegraph system with relays connected in multiple, or bridged between two sides of the line. With this arrangement it is essential to have the relay wound to as high resistance as practicable, and it may also be advisable to place additional resistance in series with each relay. Resistances are inserted between the battery, or the generator, and the line of sufficient value so that closing any one of the keys will cause the potential at all the relay terminals to fall sufficiently to cause the relays to operate. Diagram D shows a battery at one end of the line only, while diagram E shows an energy supply from both ends. This latter diagram shows the neutral points of the battery and generators grounded, and the possibility of grounding the neutral points of relays is also indicated.

Diagram F shows a combination of the metallic-circuit bridging telegraph with the metallic-circuit bridging telephone. In place of the telephone there might be substituted one of the various forms of alternating-current telegraph. This arrangement, being balanced for both the alternating-current telegraph instruments, as well as for the direct-current instruments, would be free from inductive disturbances, and similarly would not cause disturbance in neighboring circuits, a trouble frequently experienced with alternating-current telegraph systems. In other words, the two wires so connected result in two independent circuits (with intermediate stations if desired) thus providing the service facilities that the same two wires furnish when connected as simple grounded lines.

An incidental advantage of the bridging connection of telegraph lines is the ability to establish an emergency or temporary station at any point by merely attaching suitable apparatus to the two wires.

Telephone systems. As stated previously, the early telephone systems copied telegraph practice in making use of a single conductor with earth return, but since it is only in isolated cases that a grounded telephone is at all satisfactory, and since when in the vicinity of other wires it is almost invariably quite unsatisfactory, we shall, for the purpose of this discussion assume throughout that the telephone is operated on a two-wire metallic circuit.

The whole science of having a perfectly quiet telephone line is dependent on the Wheatstone bridge principle, that no current will flow in the wire or instrument connecting two points at the same potential, even though these two points are on conductors carrying currents of considerable magnitude. The practical application of this principle requires that each wire of a telephone circuit shall have the same resistance, the same inductance, the same capacity, and the same insulation resistance; and more exactly, that these conditions of equality shall hold, not only for the circuit as a whole, but for each and every short section of the circuit. Still more exactly these conditions of equality must hold for the entire range of frequency to which the apparatus is sensitive and for currents of any magnitude that are likely to be introduced into the circuit.

In practice these ideal conditions can be attained only approximately, even after making numerous transpositions of the two conductors. An Institute paper by Mr. F. F. Fowle,* dealing with the question of transpositions, and the practice of making these transpositions sections 0.5 mile long in order to reduce to a negligible amount the cross-talk from neighboring telephone circuits, shows the extreme sensibility of the telephone receiver.

The varieties of telephone apparatus, both signaling and talking, and the methods of connecting to meet various requirements, are innumerable. The two general types of magneto and common-battery systems are shown diagrammatically in Fig. 6.

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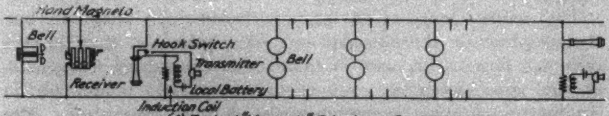
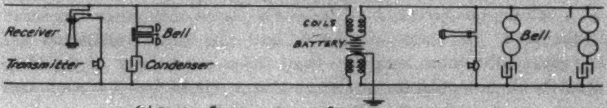
* "The Transposition of Electrical Conductors," Trans. A. I. E. E. Vol. XXII., p. 659.

Where the telephone circuit serves also for a telegraph line, the fact that the telephone is on a metallic circuit does not make the telegraph circuit metallic. For this reason, the same general considerations that apply to any telegraph line will apply to telegraph service obtained from telephone wires in the usual way.

Ringing, or calling currents, on telephone lines are commonly alternating at the rate of 16⅔ cycles per second, although lately the increased use of harmonic ringers calls for frequencies as high as 66. Hand generators are commonly wound to give between 50 and 100 volts on open circuit; this may be reduced to 10 volts or less at the end of a long line with many stations, and still be expected to ring the bell. Bells are commonly wound to 1000 ohms resistance, although many of the longer lines, with many stations use bells wound to as high as 2500 ohms resistance. The current taken by a standard 1000-ohm bell at 16⅔ cycles, 75 volts, is approximately 25 milliamperes. Fig. 7 shows the regulation of a five-bar hand magneto of standard type when connected with a load of 1000-ohm bells.



(A) Typical "Magneto" Telephone System



(B) Typical "Common Battery" Telephone System

Fig. 6

Numerous forms of protective devices are employed on telephone lines but nearly all consist of fuses and discharge gaps to ground, made up of small pieces of carbon separated by perforated mica, only a few mils in thickness. 300 to 400 volts is probably a fair figure for the breakdown point of these carbons when separated by 5-mil mica.

The actual magnitude of currents in telephone lines, resulting from speech sent into the transmitter, cannot be given with any accuracy. The strength of the battery, the special characteristics of the transmitter, the ratio of transformation in the induction coils, the constants of the line, not to mention the intensity of the voice, and the manner in which it is directed into the transmitter—all these are factors affecting the value of this current. For the purposes of this discussion, however, we may assume that on short lines the current may be as high as two or three milliamperes, while at the receiving end of long lines the current may be less than the one hundredth part of this and still be sufficient for the proper understanding of conversation.

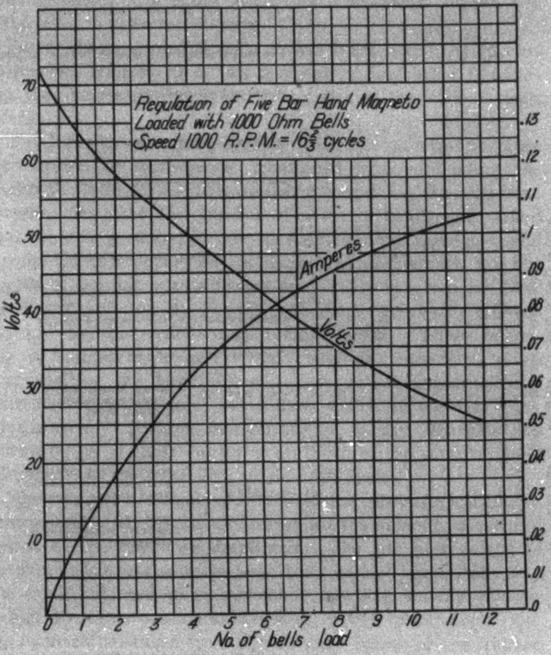


Fig. 7

The frequency of speech currents (for commercial telephone quality) is probably included between 200 and 2000 cycles. Probably the most important of these currents lie between 700 and 900 cycles. The writer believes it has been for some years the practice of the telephone companies to consider 800 cycles as the one frequency best representing the general range, and to

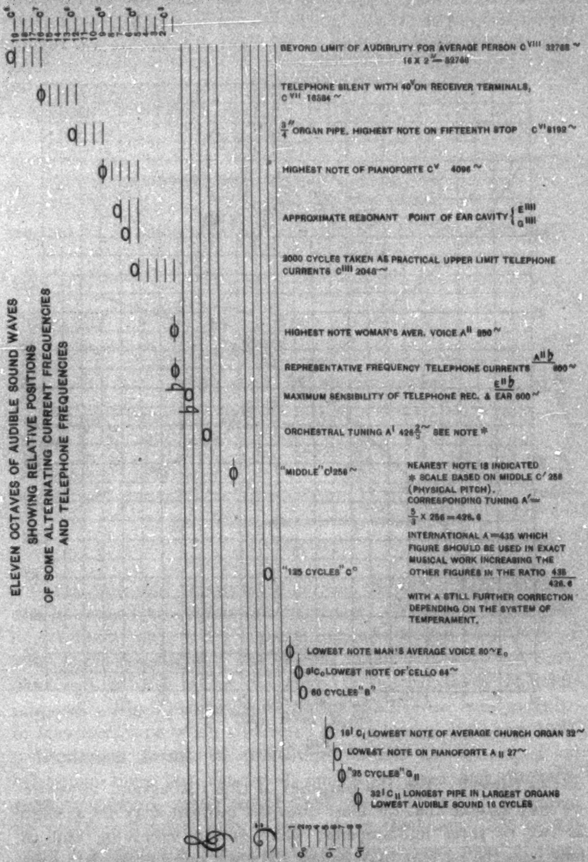

ELEVEN OCTAVES OF AUDIBLE SOUND WAVES
SHOWING RELATIVE POSITIONS
OF SOME ALTERNATING CURRENT FREQUENCIES
AND TELEPHONE FREQUENCIES
BEYOND LIMIT OF AUDIBILITY FOR AVERAGE PERSON C^{VIII} 32768 ~
$16 \times 2^{11} = 32768$
TELEPHONE SILENT WITH 40V ON RECEIVER TERMINALS, C^{VII} 16384 ~
$\frac{3}{4}''$ ORGAN PIPE. HIGHEST NOTE ON FIFTEENTH STOP C^{VI} 8192 ~
HIGHEST NOTE OF PIANOFORTE C^{V} 4096 ~
APPROXIMATE RESONANT POINT OF EAR CAVITY $\left\{\begin{matrix} E^{IIII} \\ G^{IIII} \end{matrix}\right.$
2000 CYCLES TAKEN AS PRACTICAL UPPER LIMIT TELEPHONE CURRENTS C^{IIII} 2048 ~
HIGHEST NOTE WOMAN'S AVER. VOICE A^{II} 850 ~
REPRESENTATIVE FREQUENCY TELEPHONE CURRENTS $A^{II}\flat$ 800 ~
MAXIMUM SENSIBILITY OF TELEPHONE REC. & EAR $E^{II}\flat$ 600 ~
ORCHESTRAL TUNING A^{I} $426\frac{2}{3}$ ~ SEE NOTE *
"MIDDLE" C^{I} 256 ~
NEAREST NOTE IS INDICATED
* SCALE BASED ON MIDDLE C' 256 (PHYSICAL PITCH). CORRESPONDING TUNING $A' = \frac{5}{3} \times 256 = 426.6$
INTERNATIONAL A = 435 WHICH FIGURE SHOULD BE USED IN EXACT MUSICAL WORK INCREASING THE OTHER FIGURES IN THE RATIO $\frac{435}{426.6}$ WITH A STILL FURTHER CORRECTION DEPENDING ON THE SYSTEM OF TEMPERAMENT.
"125 CYCLES" C^{0}
LOWEST NOTE MAN'S AVERAGE VOICE 80 ~ E_0
8' C_0 LOWEST NOTE OF 'CELLO 64 ~
60 CYCLES "B"
16' C_I LOWEST NOTE OF AVERAGE CHURCH ORGAN 32 ~
LOWEST NOTE ON PIANOFORTE A_{II} 27 ~
"25 CYCLES" G_{II}
32' C_{II} LONGEST PIPE IN LARGEST ORGANS
LOWEST AUDIBLE SOUND 16 CYCLES

FIG. 8

make use of this frequency from small alternating-current generators when making quantitative measurements on different pieces of apparatus. How this figure was originally arrived at the writer has not been informed, but observations of telephone speech currents, which he has carried on by the aid of the oscillograph, tend to show that, roughly, 700 cycles is the prominent frequency in a man's voice. It is somewhat higher, say 900 cycles, in a woman's voice.

Fig. 8, shows a musical scale on which are noted the various frequencies referred to in this dissertation, and other frequencies that may serve to give a clearer idea of the various tones referred to.

The difficulty of naming a value of current sufficient to cause interruption or disturbance, mentioned while discussing the telegraph system, is even greater when considering the telephone system. To state the number of years of continuous sound that could be produced by one kilowatt-hour will serve no useful purpose in this paper; but of more practical interest are the curves of sensibility to different frequencies as given by Lord Rayleigh* and by Mr. Fowle† in the paper previously referred to, and by the writer's recent experiments. These curves, Fig. 9, were all made on a different basis of comparison, which accounts for the large differences in actual magnitudes of current; but attention is particularly called to the fact that, comparatively speaking, the sensibility, at say, 25 cycles, as shown by all of these curves, is not even of the same order of magnitude as the sensibility at, say, 600 cycles.

These curves are combined physical and physiological effects, as no attempt has been made to separate the influence of natural period of the telephone diaphragm. The size and weight of diaphragms in use seem to have been derived empirically and the small difference among so many makes it worthy of note.

Fig. 10 shows oscillograph records of the vowel sound "I" (as in machine) taken from two different makes of transmitter. Curves *A* and *B* were made with the same arrangement of induction coil and transformers between the transmitters and the oscillograph vibrator, while Curve *C* was made with the same transmitter as Curve *B*, except that a single induction coil or transformer was in the circuit. The close similarity between Curves B and C show that the distorting effects of a transformation must be very small. The great differences, therefore, between Curve A and the others must be due to the difference in natural period, and amount of damping, of the two makes of transmitter.

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* "Theory of Sound," Vol. I, p. 473.

† "The Transposition of Electrical Conductors," Trans. A. I. E E. Vol. XXII, p. 659.

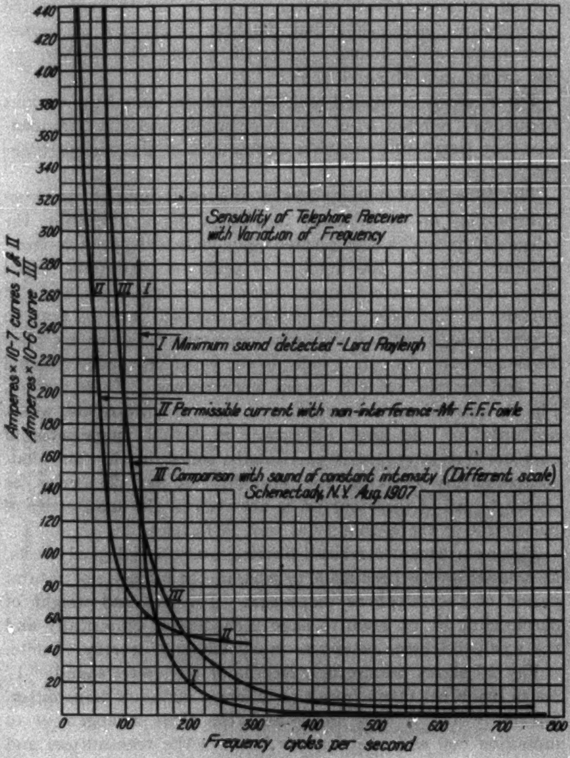

Fig. 9

Physiological phenomena having more or less bearing on this question of telephone sensibility are briefly stated below.

Fig. 10A

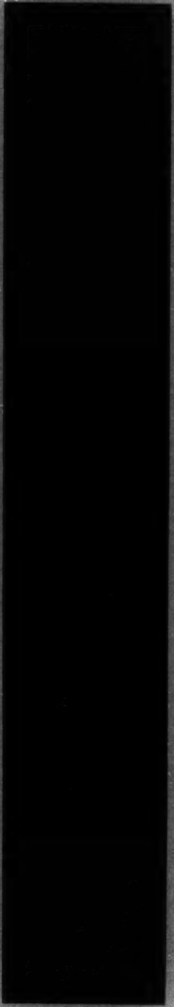

Fig. 10B

Fig. 10C

A. The lower limit of audibility is given by Helmholtz* as 25 to 30 cycles. Later investigations by Messrs Preyer and Ellis† place 15 cycles as the extreme low limit. Tests of this sort depend almost entirely on the intensity of the sound, and there is great danger in confusing some of the harmonics with the fundamental. The writer believes that he has actually heard a 25-cycle tone from a telephone receiver, but this could be heard only after taking precautions to obtain a smooth wave shape, by passing a comparatively large current through the receiver, and by holding the receiver very tightly against the ear, in a sound-proof booth. The vibration of the diaphragm at 25 cycles could be plainly felt by touching with the finger at a current value much below that required for an audible sound.

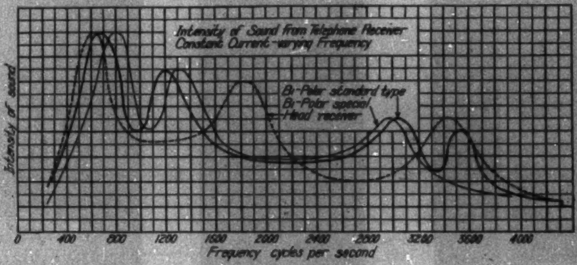

Fig. 11

B. The upper limit of audibility, while apparently more definite, varies with different observers, 30,000 cycles being the figure ordinarily assigned for the upper limit, although some persons may hear sounds as acute as those corresponding to 40,000 cycles. The telephone receiver is not well adapted to respond to these very high frequencies, and a rough test made by the writer indicated that the sound was practically lost at 12,000 cycles, even though there was a pressure of 30 to 40 volts directly on the receiver terminals. When making this experiment it was noticed that as the high-frequency generator accelerated or came to rest there were certain frequencies which gave marked increase in sound. While investigation of this point has been by no means complete, the accompanying rough curve, Fig. 11

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* "Sensations of Tone," Helmholtz, p. 116.

† "Sensations of Tone," Translator's note, p. 116.

is given as a matter of interest. While on this matter, it should be noted that for musical purposes sounds higher than 4000 cycles are considered of little or no value.

C. Low tones tend to drown out or diminish the apparent intensity of higher tones.[*] The ear apparently fixes its attention on the lower tone. This point is well recognized by musicians who rate a complex tone according to its lowest partial, even though the magnitude of this partial is small compared to that of some of the higher harmonics.

D. The ear itself, containing a column of air, should have its own natural period; this period Helmholtz places[†] in the neighborhood of e'''' to g'''', roughly, 2600 to 3200 cycles. Consequently the ear is especially sensitive to sounds corresponding to its own period.

E. Continuous sounding of a tone tends to deaden the ear to appreciate this particular tone.[‡] Consequently, there is less difficulty in talking over a noisy telephone line where the noise is of constant pitch and intensity, as compared with the difficulty of talking over a line where the noise is continually varying in pitch, intensity and quality.

Telephones for high-tension transmission line service. Quick and reliable telephone service between generating and receiving points is an important factor in maintaining service over high-tension transmission lines. Power transmission companies almost invariably have their own private lines, and usually on the same poles or structures that carry the transmission wires. There have occasionally been serious accidents to users of such telephones at the time of accidental contact between telephone and power wires; and at other times the inductive effects due to unbalanced conditions cause differences of potential between telephone system and ground. which can by no means be neglected. The telephone is, therefore, very likely to be out of commission just at the time when tangles on the power system make communication necessary in order to resume service. Various points in connection with this phase of the transmission problem were well brought out in an Institute paper[§] and accompanying discussion several years ago.

In order to safeguard the users of telephones, the telephone

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[*] "Theory of Sound," Lord Rayleigh, Vol. II, p. 444.

[†] "Sensations of Tone," p. 116.

[‡] "Theory of Sound," Lord Rayleigh, Vol. II, p. 446.

[§] "The Transposition and Relative Location of Power and Telephone Lines," P. M. Lincoln, Trans., A. I. E. E., Vol. XX., p. 245.

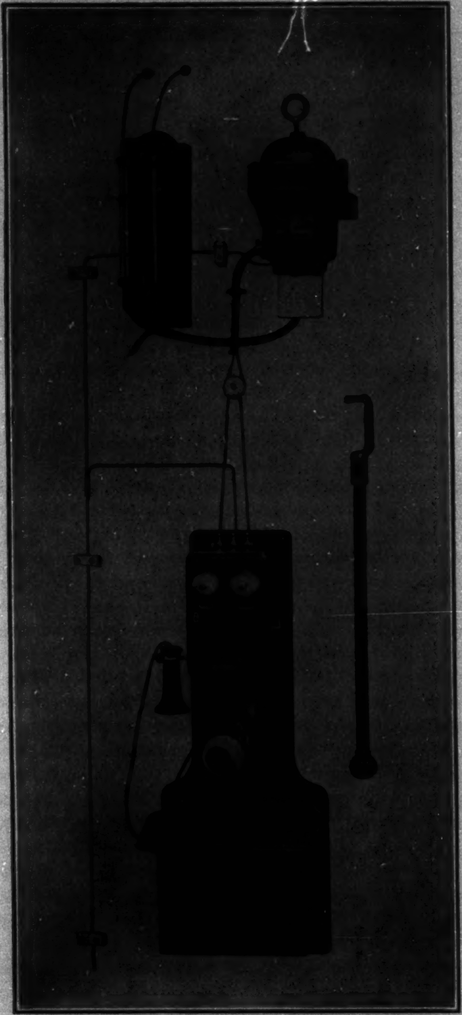
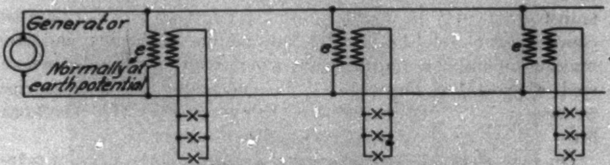


FIG. 12—Installation of telephone, with Y-109 insulating transformer and combination fuse lightning-arrester and disconnecting switch.

insulating transformer shown in Fig. 12 has been developed. This transformer is given a high-potential test of 25,000 volts between windings which come to line and those connected to instrument. The combination disconnecting-switch, fuse, and lightning-arrester, shown in the same cut, has the ordinary small-gap carbon plates across the terminals of the transformer, but such gaps are not used between line and ground. Discharge gaps to ground are made adjustable, the intention being to set these just beyond the point that the maximum induced potential, under abnormal conditions, will strike. As this potential is not likely to be much above 8000 or 10,000 volts, the 25,000-volt test insulation in the transformer is expected to protect the instrument even in the possible event of actual contact between telephone lines and wires of systems operating at 25,000 volts or higher. Both primary and secondary of this transformer may be double wound, permitting series or parallel connection, as may be best for various line conditions, and also making available a neutral point which may be grounded where such a ground is serviceable. The neutral point is of service in case it is desired to signal or telegraph over the telephone line.

On any telephone system eternal vigilance is the price of first-class service. The insulation always has a tendency to become worse, and change in resistance at connections will upset the balance. So long as the telephone line has the field to itself, the closest attention need not be paid to these points. However, when in the neighborhood of other conductors, departure from a theoretically perfect balance immediately begins to be felt, and much more attention must be paid to transpositions and insulation. While the writer states nothing new, he wishes here to emphasize the importance of bringing the insulation of the telephone system as a whole into first-class shape before wasting any time or money on transpositions. In many cases, when a telephone line becomes unsatisfactory, it is the practice to cut in more transpositions. If these have previously been located at every tenth pole, they may be doubled up, placing one at every fifth pole. Probably there are few telephone lines, on the same poles with power lines, where transpositions at every fifth pole are any more effective than at every tenth pole. While with some forms of transposition there is no objection to placing as many as the line will hold, those forms which involve cutting the wires and making splices are likely to have imperfect joints, with consequent loss of balance. In general, the more transpositions the more likelihood of high-resistance joints. We have also seen a fantastic arrangement of see-sawing the two conductors of the telephone line up and down from pole to pole in the vain hope that a noisy line would be quieted in this manner.

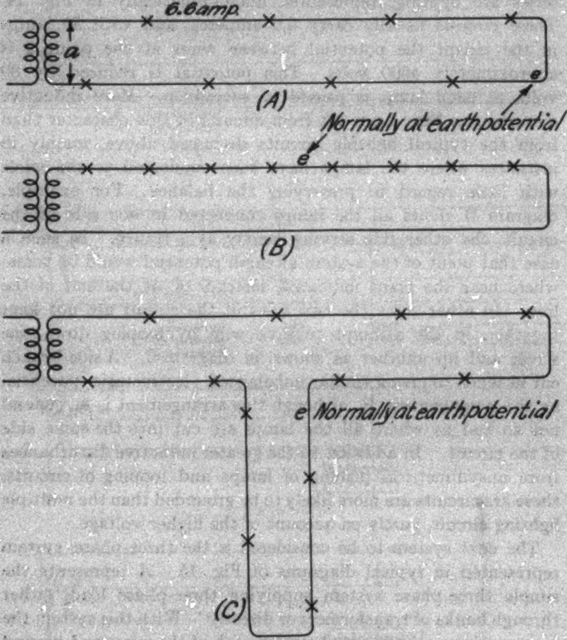
In a recent instance, additional transpositions were placed in a telephone line, and also in the power line, with small improvement in service. The trouble was eventually found in some transmitter dry batteries, which were placed away from the instrument in a damp location. It is the habit of telephone manufacturers to make common connections between the primary and secondary circuits of their instruments in the endeavor to save, either a few inches of wire, or an extra contact at the hook switch. This means that unless attention is paid to every inch of the telephone system, it is poor economy to replace the cheap pony glass on the outside line by high-grade porcelain.



Representative Diagram for Single-phase Lighting System

FIG. 13

Alternating current systems.—The earliest alternating-current systems were operated single phase and used mainly for lighting purposes, from a large number of small transformers. This system is represented diagrammatically in Fig. 13. Being a metallic bridging system free from grounds, the fields which may cause disturbance to neighboring wires are comparatively weak. Since these lighting systems usually supply the same customers that are also supplied with telephone service, local telephone lines are especially likely to be in proximity to such circuits. The further objections of property owners to tree-trimming, and to duplicate pole lines in residence sections, usually result in occasional grounds on the lighting circuit, or the telephone circuit, or both, with attending noisy lines. Since the various feeders in the local distribution are connected in parallel to the same bus-bar, a ground on any one feeder upsets the electrostatic balance of all the others. It is also possible on such a system to have a ground simultaneously on both sides of the circuit, which may result in unbalanced currents and electromagnetic inductive effects; but on account of the usually high resistance of tree grounds, etc., such currents are likely to be small and of slight disturbance compared with the unbalanced electrostatic effect.



Typical Arc Lighting Circuits

FIG. 14

An ideal metallic circuit telephone system should not be affected by exposure to fields of any strength, but the great differences between ideal and practical construction are such that not infrequently a heavy ground on a 2300-volt local lighting system will be felt on all the telephone lines in the exchange.

Another local alternating-current system is that used for series arc lighting, represented diagrammatically in Fig. 14. These circuits usually carry 6.6 amperes, and with 50 lamps in the circuit the potential between wires at the point *a* is approximately 4000 volts. This potential is reduced by 80 volts as each lamp is passed in succession. More inductive disturbances have been felt from circuits of this character than from the typical lighting circuits discussed above, mainly in instances where the lamps have been connected to the wires with little regard to preserving the balance. For example, diagram B shows all the lamps connected in one side of the circuit, the other side serving merely as a return. In such a case that point of the system at earth potential would be somewhere near the point indicated, instead of at the end of the line. In other cases the two sides of the circuit are not kept together, in the attempt to save wire by looping down one street and up another as shown in diagram C. A side-branch cut in tends to give a similar unbalanced electrostatic potential as the arrangement B, although this arrangement is in general not so bad as where all the lamps are cut into the same side of the circuit. In addition to the greater inductive disturbances from unsymmetrical placing of lamps and looping of circuits, these arc circuits are more likely to be grounded than the multiple lighting circuit, partly on account of the higher voltage.

The next system to be considered is the three-phase system represented in typical diagrams of Fig. 15 *A* represents the simple three-phase system supplying three-phase load, either through banks of transformers or directly. With this system the very nearly equal capacity between each of the wires and ground tends to maintain the neutral point of the system at earth potential as indicated by *e*. At any given instant the algebraic sum of the potentials of the three wires (measured to earth) is equal to zero, and the algebraic sum of the currents in the three-wires at any location on the system, is also equal to zero. Consequently, unless the three-wires are widely separated, the external fields, both electrostatic and electromagnetic, are weak. An accidental ground on any one of the three conductors dis-

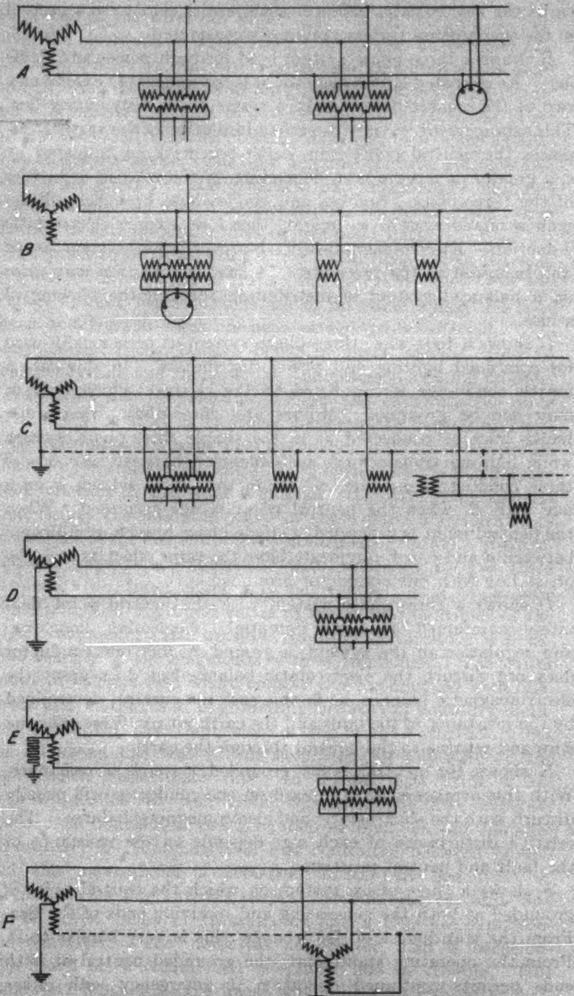


FIG. 15—Typical three-phase distributing systems.

turbs the electrostatic balance, with results similar to a ground in the single-phase system previously considered.

B shows a three-phase system used for both power and lighting. As indicated in this diagram, it is not unusual to extend any two of the conductors to make a single-phase distributing line. This arrangement, even with perfect insulation of the system, displaces the neutral point from earth potential, as indicated by *e*, a greater or less amount, depending on the relative capacities of the three-phase branches and single-phase branches. From such a mixed system we might, therefore, expect electrostatic induction. Electromagnetically, however, this system is as well balanced as the preceding. A similar condition may arise on a balanced system of distribution through the blowing of a fuse.

C shows a four-wire, three-phase system as occasionally used for combined lighting and power distribution. In this case a fourth conductor is connected to the neutral, which may or may not be grounded. Motors and three-phase transformer banks may be connected as in the simple three-phase system while lighting transformers are connected between any one of three conductors and neutral conductor. This system is on a par with *B*, when the neutral point is not grounded. When the neutral point is grounded, a single-phase branch as indicated between *d* and *e*, will obviously have the same effect as a single-phase line with one conductor grounded.

D shows a three-phase system with the neutral point definitely maintained at earth potential. Neglecting line drop and regulation of the system, a ground on any one conductor does not disturb the electrostatic balance but does upset the electromagnetic balance, as in this case the current, determined by the resistance of the fault and the earth return, flows over one wire and returns to the neutral through the earth.

E shows the neutral point grounded through a resistance. With this arrangement, a ground on one conductor will usually disturb both the electrostatic and electromagnetic balance. The relative disturbance of each sort depends on the resistance of the fault and neutral resistance.

F shows a three-phase system on which the neutral point is grounded at both the generating and receiving ends of the line. From the standpoint of disturbance, this is very similar to D. From the operating standpoint, the grounded neutral at both ends permits continued operation in emergency with either one or two of the wires out of service. When running on two wires, the electrostatic disturbance will depend on whether the third wire is alive without carrying current, or whether it is dead through being disconnected at both ends. Any operating condition which causes currents to flow from one neutral to the other through the earth, will also unbalance the circuit to some extent. In all of this discussion it has been assumed that the electrostatic capacity to ground of the generator and transformer windings is small compared with the capacity of the distributing wires whether in underground cables or overhead lines.

The practice of transposing three-phase lines varies between no transpositions at all to transpositions every mile. For the average system, transpositions are of no value unless the telephone or telegraph wires are near enough to be affected. Too many transpositions, besides being of little service, tend to weaken the line and increase the difficulties in locating trouble.

Harmonics and irregularities. When the electromotive force wave of a generator, as measured between the neutral and one of the terminals, contains third harmonics, and other harmonics which are multiples of the third, these harmonics are in the same phase relation in the three windings. Grounding the neutral point brings the potential wave of these particular harmonics on all three of the line wires in the same phase relation. Electrostatically considered, therefore, with reference to the third harmonic the three wires may be regarded as a single wire whose potential to ground varies at triple, and multiples of the triple, frequency. The possible resulting disturbance will depend entirely on the magnitude of these harmonics. The writer knows of but one case where trouble was experienced with telephone lines as the result of grounding the neutral point of generators, and in this case there was nothing to show whether or not the telephone line was in fair condition for exposure to the high-tension transmission line. In several tests made it has been impossible to tell, from the telephone line, whether the neutral connection was grounded or not. In one instance an ordinary telephone receiver was connected between ground and the neutral of a 2000-kw. 13,200-volt generator, in service and feeding, through several thousand feet of cable and six or seven miles of transmission line, a 1500 kw. synchronous converter. The noise was no greater than is occasionally heard on a commercial telephone line in trouble. This somewhat dangerous experiment was performed only after finding that the triple-frequency charging current on this system was too small to be measured on commercial alternating-current instruments.

Variable permeability and the hysteresis and eddy-current losses in transformers result in a distorted wave of exciting current. This distorted current-wave can be resolved into third harmonic components which may, for certain combinations of transformer connections, result in third harmonic potentials between three wires (regarded as one) and ground. For other connections, triple-frequency currents may circulate through a circuit made up of transmission wires and ground.

The symmetrical construction of field poles and winding of alternating-current generators causes positive and negative waves to be of the same shape, and hence free from evenly numbered harmonics.* These even harmonics, nevertheless, may be introduced into a power system if transformers or other pieces of apparatus contain iron which is permanently magnetized. Ordinarily, transformers are free from permanent magnetism, but in circuits involving earth return there may be a considerable direct current passing through the windings, derived from neighboring direct-current trolley systems, etc., Oscillogram, Fig. 16 shows the exciting current in a transformer which has, at the same time, direct current in its windings. The general tendency in such cases is for the waves to be peaked and flat topped in succession.

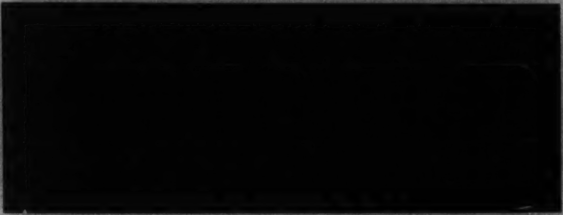


FIG. 16—Oscillogram, exciting current in 75-kw. transformer with direct current in winding. Upper curve, e.m.f. on transformer. Lower curve, exciting current

Even where the generated electromotive force wave is com-

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* See "Even Harmonics in Alternating Current Circuits," PROCEEDINGS A. I. E. E., July 1909, pp. 963–970.

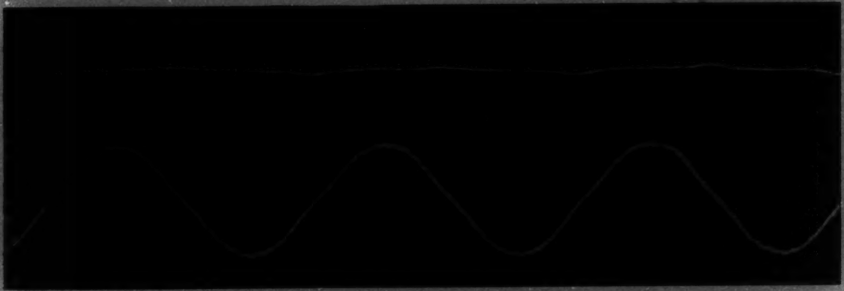


Fig. 17A—Oscillograms on single phase railway
Upper curve is current—locomotive not running. Lower curve is trolley potential

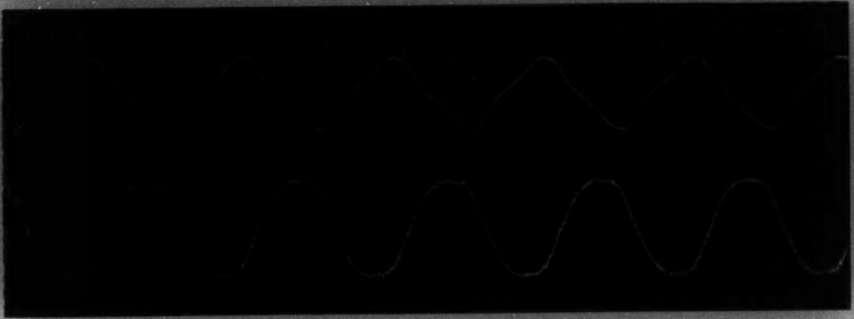


Fig. 17B—Oscillograms on single phase railway
Upper curve is current taken by locomotive. Lower curve is trolley potential

paratively free from harmonics, the various pieces of apparatus on the system will all have their effect on the potential wave. An instructive experiment on this line is to connect a telephone receiver in series with a small condenser, to alternating-current house-lighting mains. The number of strange noises heard in such a case, due mainly to induction motors on the system, will be a surprise to any one who has not tried this simple experiment.

Oscillograms in Fig. 17, show electromotive force waves on a single-phase trolley system under no load, and when commutating series single-phase motors are in operation.

Oscillograms Fig. 18 show the charging current between telephone line and ground, the same being in proximity to a single-phase trolley wire. Curve *a* is the charging current between the telephone line and ground with cars at standstill, and Curve *b* with cars in operation.

On account of the much greater sensibility of the telephone receiver to sounds of high frequency, these irregularities in the potential wave, although of much smaller magnitude than the fundamental frequency, are much more likely to be heard in neighboring telephone lines, when transpositions and other points of balance have not been given close attention. A condenser connected between alternating-current wires and earth, will, to a certain extent, absorb these high-frequency irregularities.

It should also be noted that the various neutralizing connections later discussed, as well as neutralizing for the fundamental frequency will, to some extent neutralize also for higher frequencies.

Single-phase railway. The several typical diagrams of Fig. 19 show the transformation and distribution arrangements for the latest addition to the alternating-current field—the single phase railway.

Diagram A shows the single-phase system in its simplest form. One terminal of a single-phase generator is connected to earth and the other to an overhead trolley conductor. The return circuit is made up of steel rails and earth. Neglecting line drop, the overhead conductor is at the same potential throughout and there being no neighboring conductor of opposite polarity, there will result electrostatic fields of constant strength irrespective of number of cars in operation. From the standpoint of inductive disturbances, this is the worst arrangement that can be made with the single-phase railway system. Electromagnetic effects will be proportional to the length of transmission and to current, and vary with load and distribution of cars.

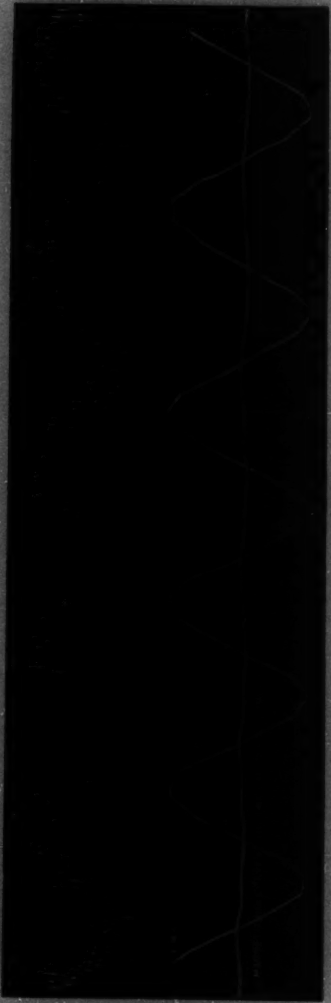


Fig. 18A

Fig. 18b

Diagram B is just as bad electrostatically, but by locating the generating station at the middle of the line, instead of at the end, the maximum length of feed is reduced to one half, and, depending on the running schedule of the cars, there may be a still further reduction in magnetic inductive effects through more or less neutralizing action from currents in opposite directions, to supply cars each side of the generating station.

Diagram C is an extension of B through the addition of transmission line and transformer sub-stations. Again considered from an inductive standpoint, this is better than B only through the feasibility of reducing the length of the individual sections. Diagram D is essentially the same as C except that transformer connections have been so made that alternate sections are of opposite polarity. Consequently, the equal exposure of a telephone or telegraph line to the same number of positive and negative sections will practically neutralize the effects of electrostatic induction. In this connection it should be noted that there will be charging currents flowing back and forth in a neighboring telegraph wire from the portion opposite the section of single-phase trolley of one polarity, to the neighboring section of opposite polarity. If there be intermediate stations on the telegraph line, these charging currents, flowing from one section of the wire to the other, may be sufficient to disturb the relay. From a railroad point of view, a section of trolley wire fed from a single sub-station is likely to tie up the whole road if a single sub-station goes out of commission. The circuit arrangement next to be considered obviates this difficulty by the use of trolley sections continuous between sub-stations, thus giving duplicate feed.

Diagram E shows a typical arrangement of a single-phase trolley wire continuous between transformer sub-stations. In this arrangement all trolley sections are of the same polarity with corresponding electrostatic effects. From the standpoint of electromagnetic induction, however, this system of distributing has marked advantages. Assuming equal transformer potential at two adjacent sub-stations, a car midway between stations will draw equal current from the two sub-stations. These equal currents flow equal distances but in opposite directions, with a consequent neutralization of the electromotive force induced in neighboring telegraph or telephone wires. This neutralization also holds for positions of the car when other than at the half-way point; for while greater current will flow from the nearer sub-station, this greater current flows through a shorter length of trolley wire than does the lesser current from the farther sub-station.

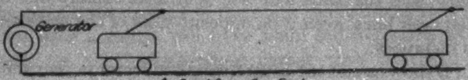
The next step is to combine the two arrangements as shown in diagram F, where trolley sections are fed from both ends, and alternate sections are of opposite polarity. This arrangement requires either two transformers at some of the sub-stations, or, what amounts to the same thing, a transformer with two secondary windings.

In the various distribution schemes already discussed, the neutralizing action, if any, is the differential effect between two or more sections. At any given point there is no neutralizing action, either electrostatic or electromagnetic. Consequently these arrangements are effective only where a telegraph line runs parallel to a number of sections at approximately the same distance.

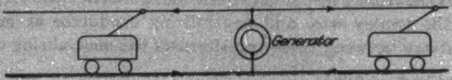
While it would be possible, it is by no means easily practicable to have a double-trolley, single-phase railway system; and, considered inductively, such a system would be on a par with any of the other metallic-circuit, alternating-current systems.

The various distribution arrangements for a single-phase railway, as shown in Fig. 19 and just considered, require no additional conductors, although the transformer sub-stations to accommodate the special arrangements may be an added item of expense.

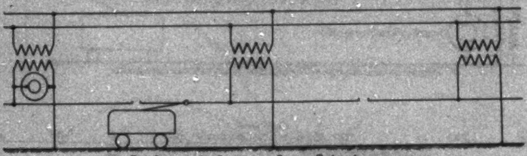
We will next consider the several distribution arrangements requiring additional conductors. Fig. 20 shows several schemes of distribution designed more or less to represent metallic circuit conditions, still retaining the single trolley. Diagram A shows a potential-neutralizing conductor erected in proximity to the trolley wire. By means of one or more transformers, this wire is maintained at approximately the same potential to ground as the trolley wire, but always of opposite polarity. Such a conductor will neutralize the electrostatic fields. It is more or less obvious that this neutralizing conductor might be placed nearer to a telegraph line than is the trolley wire, in which case a proper transformer ratio could be selected to neutralize the potential at the position of the telegraph wires. Such an arrangement, however, would be most effective for a single line of telegraph and would involve either extensive calculations or experiments to insure the best results. By having the neutralizing wire as close as possible to the trolley wire, no calculations or experiments



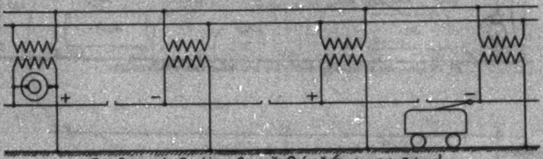
A Feed from One End



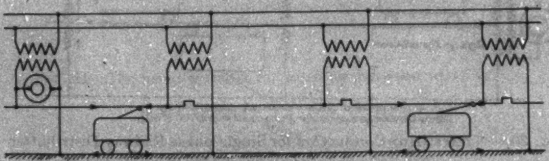
B Direct Feed, Generator at Middle of Line



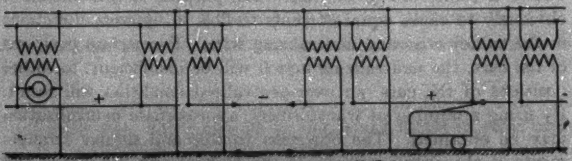
C Separate Sections, Same Polarity



D Separate Sections, Opposite Polarity (Electro-static Balance)



E Electro-magnetic Balance



F Electro-static and Electro-magnetic Balances

Fig. 19.—Distribution Systems for Single-phase Railway

are necessary, and the same wire will neutralize equally well for various telegraph lines, even if on opposite sides of the track and at various distances.

Diagram B shows a current-neutralizing conductor in proximity to a trolley wire. This conductor must be of the same carrying capacity as the trolley wire, and current transformers, ratio 1:1, are cut into the trolley wire and neutralizing conductor at intervals. Midway between these transformers the neutralizing conductor is connected to the rail. The purpose of this scheme is obviously to cause equal currents to flow in opposite directions in the trolley wire and neutralizing wire. For certain positions of the cars, the neutralizing action will be insufficient: for other positions of the cars, an over-neutralized condition will result. By using a number of transformers, approximate neutralization may be obtained. The objection to this and similar arrangements is the extra expense of the neutralizing conductor and transformers, and the greater chance of shutdown due to the

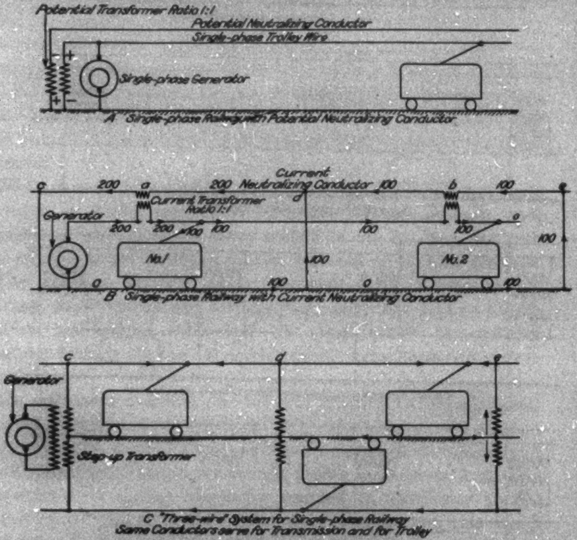

Potential Transformer Ratio 1:1
Potential Neutralizing Conductor
Single-phase Trolley Wire
+
−
+
−
Single-phase Generator
A Single-phase Railway with Potential Neutralizing Conductor
Current Neutralizing Conductor
c
200
a
200
100
b
100
e
Current Transformer Ratio 1:1
d
Generator
200
200
100
100
100
100
0
100
No.1
100
No.2
0
100
0
100
B Single-phase Railway with Current Neutralizing Conductor
c
d
e
Generator
Step-up Transformer
C "Three-wire" System for Single-phase Railway
Same Conductors serve for Transmission and for Trolley

FIG. 20.—Neutralizing Conductors for Single-phase Railway Distribution

quantity of high-tension apparatus distributed along the line. As against the expense of the extra conductor it should be noted that such a circuit will have small self-induction as compared with the usual single-phase circuit with overhead conductor

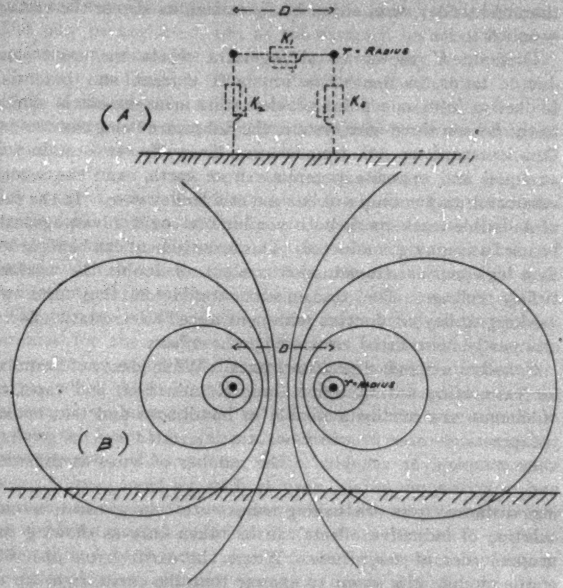


Fig. 21—The usual formula for capacity between wires is

$$C_{m.f.\ per\ mile} = \frac{0.01942}{\log_{10} \frac{D}{r}} \quad \text{(Diagram A.)}$$

This neglects effect of capacities to earth K_2 and K_3

The usual formula for inductance of a 2-wire circuit is

$$L_{m.h.\ per\ mile} = 0.0805 + 0.741 \log_{10} \frac{D}{r} \quad \text{(Diagram B.)}$$

This formula neglects the fact that some of the magnetic flux cuts the earth.

and earth return. The inductive drop will therefore be considerably less, which may be an important factor in some cases.

By installing a potential-neutralizing conductor as described in Diagram A, and a current-neutralizing conductor as well, metallic circuit conditions are approximated. A single current-neutralizing conductor of sufficient carrying capacity might serve for trolley wires over two or more tracks, and similarly a single potential-neutralizing conductor might serve for more than one trolley wire, either by increasing its size or the voltage supplied to it.

Diagram C shows an arrangement where the same conductor tends to neutralize for both current and potential. Looked at from one point of view, this arrangement is similar to the Edison three-wire system, the rail return being the neutral. Compensators, or 1:1 transformers, keep the two conductors at equal and opposite potentials from earth, and the second conductor may or may not be used as a trolley wire. In the case of a double-track road, both conductors could advantageously be used as running conductors. This arrangement can be regarded as a high-tension transmission system of double the working trolley voltage. The transmission conductors thus form two working trolley conductors with neutralized electrostatic effects, and partly neutralized electromagnetic effects.

Calculation of inductive disturbances. While plenty of formulas for calculating self-induction, mutual induction, and capacity of circuits are readily available in handbooks and text books, the practical cases in which we are interested are, in general, very complex, on account of the number of wires at different and unknown potentials, varying distance from ground, varying distance from disturbing wires, etc. In general, a calculation of inductive effects can be taken only as showing the proper order of magnitude. Where the earth forms one side of the circuit, it is usual to assume that the earth, right up to the surface, acts practically as a perfect conductor. Again, other formulas dealing with metallic circuits neglect entirely the effect of the earth, which, to be consistent with the other formulas, should still be regarded as a perfect conductor in proximity to the wires under consideration. For example; consider Fig. 21.

Let diagram A represent two conductors whose capacity is to be determined. This is given by the formula:

$$C_{m.f.\ per\ mile} = \frac{0.01942}{\log_{10} \frac{D}{r}}$$

It should be noted, however, that this formula, although that ordinarily given, does not take into account the added capacity due to the proximity of the earth. This added capacity may be regarded as composed of two condensers in series, as indicated. Where the two wires are comparatively close together and a considerable distance from the earth, this additional effect may be neglected, but as the distance between the conductors is increased the effect of the earth may predominate.

Similarly in Diagram B, consider the self-induction of the circuit made up of two conductors. The self-induction is proportional to the magnetic flux included, but it is apparent that some of this flux will pass through the earth, which still being regarded as a more or less perfect conductor, will circulate eddy currents, which in their turn set up counter-flux, thus making the self-induction of the circuit lower, the nearer the wires are to the earth. Therefore, any formula for capacity or inductance which takes no account of the relative position and conductivity of the earth must be regarded as approximate only.

The purpose of this paper is not to develop methematical formulas for the various combinations of alternating-current power circuits and telephone and telegraph circuits, under conditions which might be more or less closely realized in practice. As soon as we have to deal with more than three or four conductors, the formula becomes so complicated as to be practically unmanageable. This, taken with the fact previously stated, that all these formulas depend upon assumptions as to conductivity of the earth, etc., not actually realized, and which are unknown quantities, makes it appear preferable to present two or three typical formulas and curves for simple cases, leaving the calculation of complex circuits to those who delight more in mathematical exercises than in experimental determinations of values.

We must make some assumption regarding the conductivity of the earth, and the path taken by return current in the earth. In the usual formulas for capacity and inductance of circuits the assumption has been made that the earth acts practically as a perfect conductor. This assumption appears to be sufficiently exact, as far as the electrostatic effects with which we are interested are concerned, since the wires are usually at distances of about 20 ft. from the earth, so that the charging currents are relatively small. Even high resistance at the earth's surface could cause the potential at the surface of the earth, beneath the wires, to differ but very slightly from true "earth" potential.

Return currents in the earth, however, are of an entirely different order of magnitude, so that the path taken by this return current will tend to be that which offers the least resistance. This return path of lowest resistance will be modified by the fact that the farther the return circuit is from the overhead wire, the greater will be the inductive drop, which, in its turn, will tend to cause current to flow nearer to the line conductor. The actual or effective return, therefore, will be

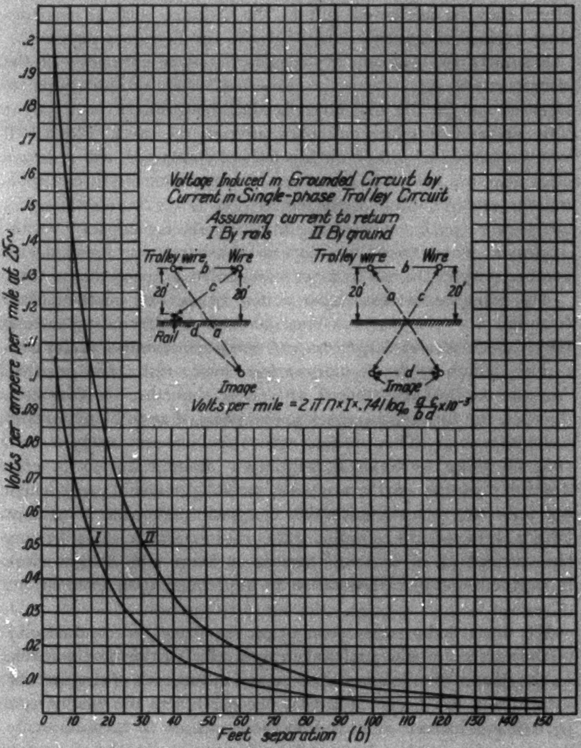


FIG. 22

determined by a combination of resistance and inductive effects, in a given case depending largely on nature of soil, amount of moisture at different depths, proximity to bodies of water,

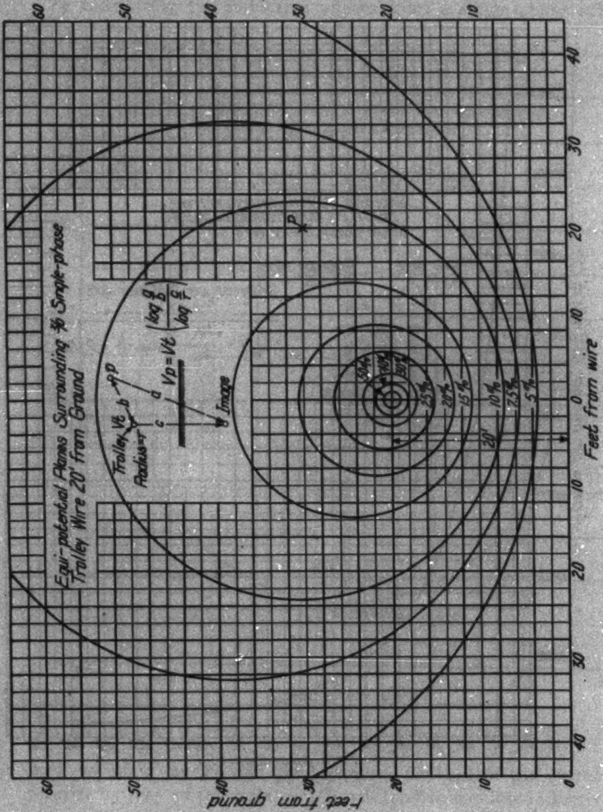


FIG. 23

water mains, gas mains, and rails of neighboring traction systems.

However, in order to deal at all with the question, it is necessary to make one assumption or the other; either that the earth is an insulator or a perfect conductor. The various formulas are based on the latter assumption. With this assumption it can be shown that the effect of distributed charge or current is the same as though this charge or current were concentrated on a

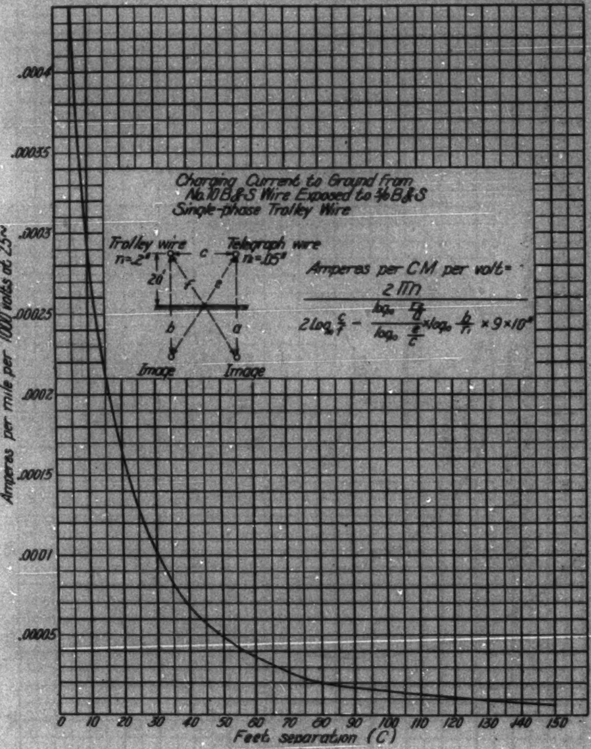


FIG. 24

wire as far below the ground as the wire in question is above the ground; in other words, on what would be the "image" of the overhead conductor if the surface of the earth formed a mirror. This means that where the earth forms a return circuit to a conductor 20 ft. in the air, the effective separation of the two conductors, and hence the self-induction, will be that corresponding to a two-wire circuit with conductors 40 ft. apart instead of 20 ft. apart.

In calculating the inductive effects from a single-phase rail-

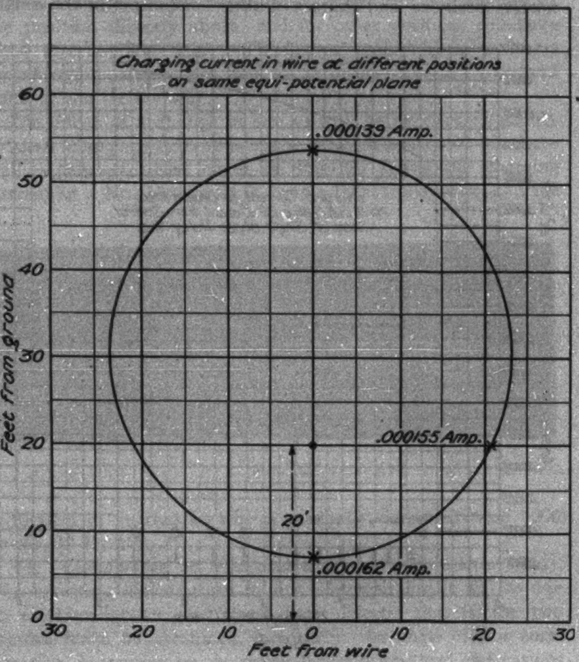


FIG. 25

way, we may, on the one hand, assume that all of the current returns by way of the rails, which will lead to too low inductive values, as some of the current is almost certain to leave the rails and return by way of the earth. On the other hand, the image assumption may also lead to too small inductive values on account of the imperfect conductivity of the earth. The true inductive value, therefore, will be influenced by the amount of current leaving the rails, and also on the effective path taken by this current. In the absence of definite experimental determination of inductive action in and from a given circuit, we usually assume the image as the effective return conductor.

The electrostatic potential at any point depends on the relative positions and charges of other conductors in the neighborhood. The charging currents, therefore, flowing into a grounded wire will not be the same when it occupies different positions, even though the potential on the wire when insulated is the same for the different positions considered. This is because of the reaction of the induced charge. For example, Fig. 26 is taken from Fig. 23, and the circle represents the 10 per cent potential surrounding the 000 trolley wire 20 ft. from the

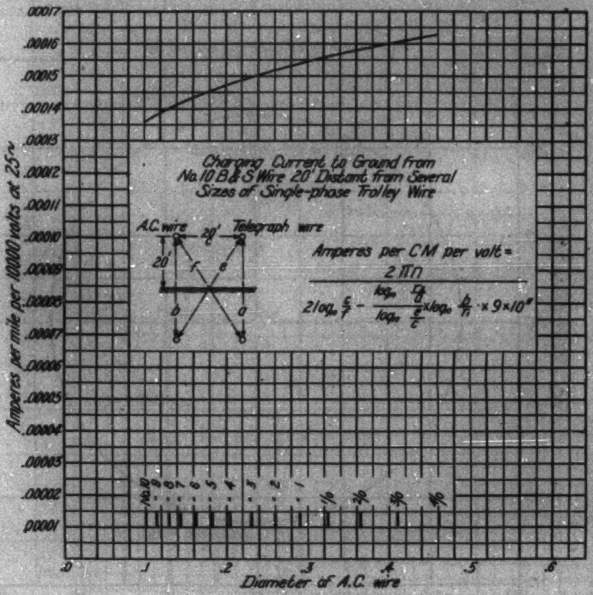


FIG. 26

ground. A wire occupying any position on this circle would show the same potential to ground, if measured by an electrostatic voltmeter. However, the charging current when the wire is grounded will vary for different positions on the circle. This charging current will be a maximum when the wire in question is directly below a disturbing wire, and a minimum at the position directly above, and for other positions will have some intermediate value. The figures against three positions are charging current per mile at 25 cycles for each thousand volts of the trolley wire.

The effect of a change in size of wire on an electrostatically induced charging current is slight, provided the two wires are well separated. The curve in Fig. 25 shows the charging current in a No. 10 wire 20 ft. from a 0000 trolley wire, and the reduction in current as this is gradually decreased from 0000 to No. 10 B. & S.

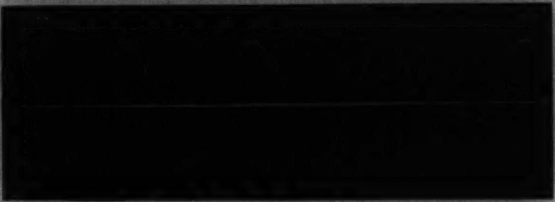


Fig. 27

VI. *Comparison of electromagnetic and electrostatic effects.* The resulting disturbances in any telegraph circuit will be due to electromagnetic and electrostatic effects; that is, the two factors must be combined vectorially, the angle of this combination depending on the power-factor of the load and various constants of the telegraph circuit. Oscillogram Fig. 27 shows current in a single-phase trolley circuit, and electromotive force induced thereby in a neighboring telegraph loop. The high-frequency irregularities on the induced wave are due to the addition of electrostatic effects. The current in the circuit due to electromagnetic induction will obviously be a maximum when all the keys are closed. An electrostatic charge will flow in from both ends of the line when all keys are closed; under other conditions this charge must all be supplied from the ground at one end of the line. It should be obvious, therefore, that the nature of the disturbance experienced will depend on whether electromagnetic or electrostatic induction is the predominating factor. Below are given in parallel columns some of the features of electromagnetic and electrostatic inductive effects.

TABLE I

Electromagnetic	*Electrostatic*
Varies with load.	Constant effect.
Varies with position of car.	Independent of position of load (neglecting line drop).
Induced electromotive force in proportion to frequency.	Open circuit potential (to ground) independent of frequency. Charging current if grounded, in proportion to frequency.
Induced electromotive force proportional to length.	Open circuit potential (to ground) independent of length.
Current in closed telegraph line practically independent of length. (Assume total impedance increases proportional to length.)	Charging current, when grounded proportional to length.
Induced current in instruments greatest when a l keys are closed.	Charging current in some instruments greatest when distant key is open.
Practically same current in all instruments.	Current a maximum in some instruments, while zero in others.
Line resistance and reactance an important factor limiting current.	More in the nature of a constant current effect.
Generally the predominating effect in telegraph lines.	Generally the predominating effect on telephone lines.
Slight shielding action obtained from neighboring conductors.	More effective shielding action from neighboring conductors.
Slight shielding obtained by placing in lead-sheath cables, or by placing underground.	Effective shielding by use of lead sheath cables.

SUMMARY

All working conductors are surrounded by electromagnetic and electrostatic fields. These fields induce electromotive forces and charges in neighboring conductors. With an ideal metallic circuit, external fields are a minimum. Similarly, an ideal metallic circuit may be in fields of any strength without being disturbed.

Practical considerations prevent these ideal conditions from being realized. Hence currents will be induced in any conductors wherever placed as a result of currents and potentials on other conductors. Disturbance results only when these induced currents are of sufficient magnitude to be objectionable.

Commercial telephone lines have little margin to meet disturbing conditions more severe than normal. An increase of telephone currents to three or four times their present values would doubtless result in great disturbance to other wires in the same telephone system and require new standards of construction and maintenance. The same statement applies to telegraph systems.

Theoretically a balanced telephone line can be operated in proximity to alternating-current wires. This is not true of a telegraph line, as there is no way of balancing a circuit that uses earth return.

Where trouble is experienced on a telephone line it may be possible to clear the line by putting the system in first-class condition. Where trouble is experienced on a telegraph line, some change in the apparatus or circuit arrangements will be necessary.

For any given case, all the features of the power system and signaling system should be taken into account with a view to arriving at the proper procedure to reduce or to eliminate the disturbances.

DISCUSSION ON "TELEGRAPH AND TELEPHONE SYSTEMS AS AFFECTED BY ALTERNATING-CURRENT LINES." NEW YORK, OCTOBER 8, 1909

President Stillwell: From the earliest days men have found themselves discussing and frequently quarreling over property interests. In comparatively modern times the question of right-of-way has been raised frequently in an acute form as between railroads and streets and wagon roads belonging to municipalities or townships; and for a considerable number of years also, more especially in Europe, there have been questions in regard to what I may call aerial rights-of-way, the right to sunlight intercepted by the erection of buildings.

The question of right-of-way in ether is strictly modern. It arose first in the shape of damage caused by electrolysis, due to the utilization of the earth by electric railways, as return conductor for the currents used for motive power; the electrolytic action set up by these currents causing, in some cases, more or less damage to existing sub-surface structures. This interference has raised and is still raising some interesting questions in regard to prior rights. These questions have not been fully adjudicated, but the courts in general have decided substantially that no individual interest can own the earth; that adjustment must be sought along reasonable lines; and that the principle of give and take must be recognized.

It is the business of scientists, particularly of those who have to do with applied science, as have the members of this Institute, first to ascertain the facts in any case of this kind and then to seek by scientific means to eliminate causes of conflict; in brief, to find a cure, or a preventive, rather than to let the conflicting property interests go to the length of opposing each other in the courts. The procedure should be science first, and then, if science cannot find a cure, the principles of justice and fair-play may be relied upon to effect a final adjustment. It is highly important, I believe, that engineers should take the reasonable and just view and not the partisan view on questions of this kind.

The action of a committee of the American Water Works Association some years ago illustrates the opposite policy. The recommendation of that committee was adopted by the association named, and it stands to-day as the pronouncement of that association in regard to what should be done in respect of conditions that cause electrolysis. The position is unsound and could not be maintained for a moment in a court of justice. That an engineering body, or a quasi-engineering body, should take a position unsound and unreasonable is unfortunate. The position taken amounts, in effect, to a declaration that electric railways shall not be permitted to use a grounded return; that they shall keep off the earth and shall double trolley all lines.

We are fortunate in this Institute in having a membership that is interested primarily in scientific facts, and in finding reasonable and effective remedies for difficulties as they arise. I have very great pleasure in introducing Mr. J. B. Taylor, who will read the first paper before the Institute on this interesting apparent interference with the operation of telegraph and telephone systems by parallel alternating-current power circuits.

Charles F. Scott: The interference between electric circuits is of three fundamental kinds. An adjacent circuit may receive from an alternating-current circuit: 1, effects due to leakage; 2, effects due to electrostatic induction; and 3, effects due to electromagnetic induction. These interferences are not separate and independent, but are often intermingled in an intricate and confusing way. A brief reference is made in the paper to a method of neutralizing the effect of a single-phase railway circuit upon an adjacent telegraph circuit, which I have been personally much interested in and will therefore describe in some detail.

Some years ago it was recognized that the inductive effects produced in a circuit adjacent to a single-phase railway in which a large current is carried a long distance would probably cause disturbances in the adjacent circuits, and that these disturbances could not reasonably be avoided by readjustments or modifications of the circuits in any simple way. When, therefore, the inductive action is likely to go beyond moderate limits, some means becomes necessary for counteracting its effects in the telegraph wires. From the information and experience at hand at that time I concluded that the electromagnetic induction would be the most serious element, and I set about to devise some method of counteracting it.

The first and most obvious arrangement that presented itself is one to which Mr. Taylor has referred, in which a transformer has one coil in the trolley circuit and a second coil connected in series with the telegraph wire in such a direction that the electromotive force of the secondary of the transformer opposes the electromotive force induced in the telegraph line. This is in effect a special form of transposition. In ordinary transposition the adjacent sections of the circuit are transposed so that the induction in one section opposes that in the adjacent section. It is impracticable, however, to transpose a telegraph line with earth return, so additional sections in the form of transformer secondary coils are introduced which can be reversed; each section of line in which an electromotive force is induced by the current in the railway circuit is followed by a transformer secondary coil in which an equal and opposite electromotive force is induced by the current in the primary coil.

This plan might serve for a definite fixed condition, but railway operation unfortunately involves many variables. As the load is shifting, induction in the telegraph wire will change continuously as the train moves, while the induction in the transformer changes instantly when the train passes it. Moreover, the induction in the telegraph line is not proportional to the current in the trolley wire, but depends also upon the proportion of the current which flows in the rails and that which flows in the earth. This variable proportion is dependent upon the number of tracks, the distance from the train, and other conditions.

I then proposed to wind the primary of the transformer differentially by including certain turns in series with the trolley and other turns in series with the rail, so as to make the electromotive force induced in the transformer more nearly equal to that induced in the line. While this did not offer a complete remedy, it appeared to be a step in the right direction and worthy of trial. I turned the matter over to Mr. A. J. Sweet, asking that he design a transformer for trial test. In a few days he reported that he had studied out a modification that would overcome the fundamental objections to the transformer with double primary coils. He then described a method, that was adopted on the telegraph circuits paralleling the electrified portion of the New York, New Haven & Hartford Railroad. The method is briefly referred to in Mr. Taylor's paper.

A neutralizing circuit having practically the same exposure as the telegraph wire is employed as the primary circuit for supplying the neutralizing transformer. This in turn gives a secondary electromotive force practically equal to that induced in the telegraph wire. The two are connected in opposition. A careful study of this system brought out its many advantages. Experimental tests were made, both in the laboratory and in connection with a single-phase interurban railway on which, during the tests, very heavy currents were employed in order to induce a considerable electromotive force in the circuit under test.

In order to appreciate more fully the intricate problem which is presented it is interesting to note the principal variables that affect the electromotive force produced in an adjacent wire:

1. The current in the trolley wire, the amount of which varies with the load.

2. The current in the rails. The return current divides between rails and earth in different proportions under different conditions.

3. The current in the earth and the effective position of this current. Suffice it to say that the actual effective current does not flow where the mathematical image directs, but diffuses itself in accordance with unknown physical conditions within the earth and scarcely less mysterious laws of distribution.

4. The phase of the current, which is not the same in the trolley, the track, and the earth.

5. The length of exposure, which depends upon the varying position of moving trains.

6. The distance from the railway or primary circuit to the telegraph wire. In a road with two or more tracks, any one of which may be in service, the effective distance is liable to change without notice.

Now all of these variables have their effect upon a telegraph wire, and there is no other place where a like effect is produced. Therefore, a circuit on the same poles that carry the telegraph wires—and having therefore substantially the same electromotive force in it as is induced in the telegraph wires—should be made to introduce a counter electromotive force in the telegraph wire, so that the counter effect may vary in the same way as the initial effect. When the transformer primary coil is connected in series with the neutralizing circuit, the electromotive force produced upon a secondary coil having the same number of turns as the primary will be slightly less than the induced electromotive force in the primary circuit on account of the drop due to resistance of the neutralizing circuit. In order that the electromotive force on the secondary may be equal to that induced in the telegraph circuit, it is obviously necessary to have a few more turns on the secondary coil than on the primary. By using a suitable number of turns, the electromotive force on the secondary is made practically identical with the electromotive force in the telegraph wires. The tendency for alternating current to flow in the telegraph circuit is therefore eliminated. As a matter of fact, there is a slight difference of phase between the secondary electromotive force of the transformer and that of the telegraph wire. Methods have been proposed, and tested, for reducing or eliminating this difference of phase, but it has not been found necessary in practice to employ them.

As the secondary coil carries no alternating current, the transformer acts as if on open circuit. The transformer may therefore carry a number of secondary coils, each connected to its own telegraph circuit. It is found that the secondary coils introduce but little impedance into the telegraph circuits, and that the increased mutual induction between telegraph circuits is inappreciable.

The arrangement and capacity of the neutralizing transformer are adapted to the particular conditions in which it is to be placed. The neutralizing circuit is grounded just beyond the ends of the exposed section. If this is long, two or more neutralizing transformers may be installed, and the neutralizing circuit may preferably be grounded midway between adjacent transformers.

Some time before the electric service was inaugurated on the New Haven road, the engineers of the telegraph company made inquiry in regard to the conditions which might be anticipated. These conditions were discussed and the above-described system of neutralizing transformers was explained. Tests followed, and a request was made for general specifications for the installation of the system. This was prepared and a transformer was designed for the service. An order was placed for a number of transformers about a year before the electric service was started. The transformers were built and installed and are now operating as originally designed. The transformer is of the simplest type and is adequate for handling a large number of telegraph circuits. The transformers along the New Haven road are arranged for the accommodation of thirty telegraph wires. Preliminary tests were made by A. W. Copley as soon as current was available, in order to determine the best ratio of primary and secondary turns and to observe the operation of the system. It was found that the residual electromotive force is only a few per cent of the induced electromotive force. It was also noted that the neutralization became less effective when a large number of telegraph circuits were connected. It was found that the direct current in the telegraph circuits magnetized and saturated the core of the transformer, which in turn increased the primary magnetizing current and the loss in the primary circuit. This could be obviated by reversing the battery on part of the telegraph circuits or by introducing an auxiliary direct-current coil. These precautions have, however, not been introduced in practice.

It may be noted in connection with this system that it is independent of the railway circuits. There is no introduction of coils into the trolley or the rail circuits. There is no danger of connection between trolley circuits and telegraph wires due to defects in the transformers. There are no moving parts or elements requiring adjustment.

It was found that the electrostatic effect upon the telegraph wires, although paralleling a 10,000-volt trolley at a distance of only a few feet, appears to be nil on the New Haven system. This is presumably due to the considerable number of telegraph wires which probably distributed the charge among themselves, and, as these wires are grounded in regular service, the effects due to electrostatic induction have introduced no serious effects, and, indeed, have failed to be discovered.

Mr. Taylor's paper is, as he states, a general one and introduces a number of suggestions indicating an academic standpoint, as they are suggestions illustrating the principles involved in certain theoretical methods rather than methods to be carried out in practical specifications. Nevertheless, I think it not unlikely that some of his suggestions might be taken by persons not familiar with engineering conditions as rather simple and easy remedies for overcoming all practical difficulties. For example, it is very easy do draw on a diagram a potential neutralizing conductor parallel and close to a trolley wire; but the running of a second conductor having a difference of 20,000 volts in potential from a trolley, and maintaining it in close proximity to the trolley wire, is easier on paper than it is over a railroad. Again, the suggestion is made of running a second wire for carrying the return current. It is not a simple matter to support and maintain a heavy grounded conductor near the trolley wire. With regard to the arrangements that I am just referring to, the middle diagram of Fig. 20, shows a transformer electrically linking the trolley wire and an overhead return conductor, the purpose being to carry the return current by the overhead conductor instead of by the track; and it is stated on the top of the next page that the inductive drop may be considerably less than with the earth as a return, which may be an important factor in some cases. I doubt whether under practical conditions that would be found to be so. True, the two conductors are fairly close together; but when the track and the earth constitute one conductor, it is of such large diameter that the self-induction of the circuit is due principally to the overhead conductor.

If, then, the two wires—one the trolley wire and another wire of the same size—be placed, say, two feet apart, the self-induction of the circuit will be somewhat in excess of the self-induction of a circuit consisting of the trolley wire and the track return. The resistance lost in the track and earth return is usually quite small compared to that in the trolley wire. A second wire overhead for the return of the current will considerably increase the resistance lost in the circuit. If that resistance loss is about the admissible limit, then adding a second wire would tend to double that loss; hence the size of the conductors would have to be doubled, making the total weight of the conductor in the trolley and in the return some four times as great as that required in the trolley alone, when the track and earth return is employed.

I notice at the bottom of Table I, under electromagnetic induction, the statement that a slight shielding action is obtained by placing wires in lead-covered cables, or by placing them underground. That is, I think, correct if it is understood that ordinarily the effect is a very small part. I have found many persons who think that if any overhead wire were buried, all of its troubles would be a thing of the past and that electromagnetic induction would not seek it in the earth. On the other hand, the electromagnetic lines which surround a conductor are not affected by the earth, so that whether a wire is placed a little above or a little below the surface of the earth does not make much difference. Thus if a cable is 20 ft. from the trolley, and is midway in height between track and trolley, it does not matter whether the ground is low and the cable is supported on poles, or whether there is a high bank at the side of the track and the cable lies in the earth. It is the position of the cable and not the position of the earth which is of consequence. There may be a little flow of current in the lead shield which will tend to neutralize the field, but that is of minor effect. So that speaking generally, the burying of a wire in a lead-covered shield or cable has, I think, very little effect in reducing the electromagnetic induction.

A. W. Copley: I have had an opportunity to make extensive experimental investigations on the New York, New Haven & Hartford Railroad to determine the nature of disturbances in neighboring telegraph lines caused by current in the railroad power circuit, the causes of such disturbances, and to suggest remedies therefor. In the light of the results of these experiments, there are several points in the paper to which I wish to call attention. Mr. Taylor has given some data for the amount of alternating current that caused chattering in one particular telegraph relay with one particular adjustment. He has said that it is impossible to make a general statement covering all the various conditions of instruments and circuits.

I wish to give similar data obtained by me on artificial lines that were made to approximate closely several conditions obtaining on actual lines. Bad weather conditions were approximated by placing leakages between lines and ground. Several different adjustments were made on the telegraph instruments by a telegraph expert when there was no alternating current in the line, these adjustments being made to correspond with what might be met with in practice. After each adjustment, alternating current was introduced into the circuit in increasing volume, until it began to affect the working of the instruments. The ratio of the alternating voltage to the working direct voltage was then taken. This was tried for alternating currents of both 25 and 15 cycles, and on simplex, duplex, and quadruplex circuits.

The first tests, on simplex circuits were made with box relays in the circuit. These are relays which act as sounders, and with them no local circuit is necessary. These relays showed the effects of the alternating voltage at very low values, the signals becoming uneven and "mushy." This is because the relay gives a sound proportional to the strength of the blow of the armature, and the alternating current varied this strength so as to make some signals strong and some weak. The box relays are seldom used in actual circuits, and therefore no data were recorded under this condition.

The usual simplex circuit uses neutral relays that close local sounder circuits. With these the intensity of the armature stroke has little to do with the distinctness of the signal. Tests made with these relays gave the ratio of allowable alternating voltage to direct working voltage as about 0.5 for 25 cycles, and 0.4 for 15 cycles. The ratio was found not to vary greatly from these values with considerable variations in the circuit conditions, and adjustments of the instruments. Duplex circuits were less sensitive: the ratio in this case averaged 0.9 for 25 cycles, and 0.7 for 15 cycles.

Quadruplex circuits were by far the most sensitive, and showed a great deal of variation; but average values of 0.2 and 0.15 were obtained for the ratios at 25 and 15 cycles respectively.

Results on actual lines confirm closely the above results. Thorough tests in actual lines were made with simplex circuits, but only limited tests were made with either the duplex or quadruplex on actual lines—the ratios given are, of course, only approximations, but they may be taken as practical working limits. I would add, further, that although the allowable 15-cycle voltage is only about 75 per cent of the allowable 25-cycle voltage, the voltage induced by a given amount of current at 15 cycles is only 0.6 of that induced at 25 cycles. Therefore the telegraph lines are slightly better off under the influence of the lower frequency.

It is seen, then, that the disturbance can be overcome if only the working direct voltage is made high enough; this is quite an effective method as long as the direct current is not increased above allowable limits. The method is substantially the same as the second remedy given by Mr. Taylor; that is, increasing the working current. If it is undesirable to increase the current, but increase of voltage is allowable, a combination of his first and second methods may be used—increasing the impedance or resistance of the lines, and at the same time the direct voltage, holding the current constant.

The last remedy, the bug-trap arrangement, might be emphasized. Tests made with this device showed that it was possible to work a simplex line in which the alternating induced voltage had several times the value of the direct voltage; but it was found to be inapplicable to cases where the alternating voltage varied. If the induced voltage is steady the arrangement is quite efficient; if not, the relays must be constantly adjusted.

The reason for the good performance obtained is that as the contact in the local circuit is made on the back contact of the relay, the local circuit is always definitely closed when the sender's key is opened, at which time no current, either alternating or direct, is flowing through the relay. With the sender's key closed, the armature of the relay chatters against the front contact, which is dead, but does not rebound far enough to touch the live back contact. Therefore the local circuit is definitely opened.

The other remedies suggested have been tried, but with little success.

Mr. Taylor has devoted several pages to the calculation of inductive disturbances. He has indicated the importance of knowing the positions and the volumes of the currents in the various parts of the circuit. In particular, it is necessary to know the volume and effective position of the earth current. By effective position I mean the position at which, if all the earth current were concentrated, the same inductive effects would take place as do actually occur. This will be different for wires at different distances from the road, because of the wide distribution of current in the earth. Tests have shown, however, that it can be assumed for practical calculations at one position for wires within a considerable distance.

From theoretical statements in Mr. Taylor's paper, it appears that part of the return current would be found in the rails and part at the image of the trolley wire. But tests made on the New Haven road and at other places indicate that the effective position of the earth current is far below this image; in fact its depth is in the order of ten times the depth of the image.

The amounts of the rail and earth currents were investigated, and the results have been published as part of my discussion of a paper by J. B. Whitehead at the Atlantic City Convention, in 1908.* The figures were also published in the November, 1908, *Electric Journal.* When it was found by test on single-track roads that the earth current was as high as 60 per cent of the trolley current, calculations were made which closely verified this result. Charles F. Scott at that time made calculations for two- and four-track roads, in which the effective diameter of the overhead conductors and the track are much greater than in a single-track road. This condition naturally produced a different magnetic field in the earth below the track, and a different distribution of the earth current, as well as a different ratio between rail and earth currents. The result of the approximate calculation led us to expect about 75 per cent rail current. Subsequent tests showed 80 per cent.

Mr. Scott stated in an editorial in the *Electric Journal*, in November, 1908, that the earth current is largely due to inductive rather than to resistance effects. Supposing the track to be insulated from the earth, and an insulated wire to be buried at a depth of several yards under the track, one end of the wire being connected directly to the rails—then a voltmeter connected between the other end of the wire and the rails will measure a considerable induced secondary voltage. This is in addition to the resistance drop in the rails, the primary circuit being the trolley wire and rails, and the secondary circuit the rails and the buried wire. If the voltmeter be short-circuited, a current will flow in the underground wire. Similarly the earth acts as a connection between the ends of the track, and if the latter be not insulated, current will flow from the rails into the earth.

In Fig. 22 Mr. Taylor gives curves, showing the induced electromotive force in neighboring circuits for the two conditions of all current returning by rail, and all returning at the image of the trolley wire. As the effective position of the earth current has proved to be so much lower than the image, and the amount of this current is fairly large, the curves are of little value practically. It is not, however, impossible to fortell approximately the induced electromotive force in a telegraph line. From the tests made on single-track roads we were able to calculate an effective position of the earth current, and from this, together with the calculated proportion of earth current, it was possible to calculate the voltage which might be expected on the New Haven railroad. The actual induced voltage checked to within 10 per cent of the values calculated a year before current was put on the line.

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*Proceedings, A. I. E. E., December, 1908, p. 1733.

W. S. Murray: I think the best way to discuss this subject, at least from the railroad point of view, is to confine my remarks as closely as possible to the actual facts of the situation. The New York, New Haven & Hartford Railroad Company in their electrification zone has certainly greatly abused the adjacent telegraph and telephone lines by inflicting them with inductive troubles. Without diminishing one iota the meritorious achievements incident to the invention and use of the telegraph and telephone, yet I believe that public opinion, in estimating the usefulness of these three great agents of convenience, would grant, and not unselfishly, in the sense of "the survival of the fittest", both written and unwritten rights to the railroad. I do not mean to intimate that, by virtue of its predominance over the other two conveniences the railroads should be permitted to abuse their rights and privileges; but if real progress is to be considered, the value of things must be regulated by their importance, and while apparent injustice sometimes may be rendered in the working out of this law of order, in reality public rights of convenience have been conserved.

Mr. Taylor's paper interests me in three different ways: first, because the information presented is concisely stated, and shows the hard work of the author in his effort to offer something useful; secondly, it gives me a clear picture of the troubles that the telegraph and telephone companies have had with a commodity we give them, that in the giving does not cause us any trouble at all; and, thirdly, because I am interested in a single-phase, alternating-current railway that, on account of the arrangement of its circuits, gives to the telegraph and telephone wires in its vicinity the maximum amount of inductive troubles.

Ever since alternating current was transmitted over wires it has been a nuisance to nearly every other electric circuit in the immediate neighborhood. Its only saving grace has been its association with things of maximum importance. The mitigating excuse for its existence is it accomplishments.

Familiar ground is covered in that part of the paper which is confined to the several schemes of arranging wires to neutralize both electrostatic and electromagnetic induction. All of these arrangements were considered during the preparation of our electrification plans. Distribution by polyphase circuits and reversals of direction of current flow by the transformer method were both considered; but all economic features were met, as far as the transmission system was considered *per se*, by the distribution of a single voltage in a single-phase throughout the complete system. Though conscious of the fact that this decision prescribed severe inductive troubles upon the lines of the adjacent telegraph and telephone companies, yet in the same moment of this decision we united with them in a search to find the remedy for their difficulties. The cost to the railroad company partly to eliminate the inductive effect of its power circuits would be many times that to the telegraph and telephone company to guard against this effect. Mr. Taylor's paper intimates this conclusion; our actual calculations justify it.

In regard to the summary given at the end of Mr. Taylor's paper, I am in agreement with the statements made in the first paragraph, except the last sentence. It seems to me that the ideal metallic circuit, if subjected to a magnetic field, would be disturbed to the extent of having its potential raised above the earth; for example, one standing on the ground and touching the circuit would receive a voltage in proportion to the frequency, length of circuit, and number of lines of force cut.

I agree with the second paragraph.

I agree with the third paragraph, assuming that no auxiliary apparatus is used to meet the disturbing condition.

I agree with the first sentence of the fourth paragraph, but ask if the compensating transformer that derives its primary voltage from both earth and wire potential does not virtually provide a secondary voltage in complete compensation for voltage in the telegraph wire and its ground return?

I agree with the fifth and sixth paragraphs.

In order to ascertain the actual conditions that exist to-day, and give some line on the results obtained in an effort to compensate for the induction suffered by lines adjacent to our electrification, on Tuesday, October 5—a few days ago—a conference was arranged, at which were present Messrs. N. E. Smith superintendent of telegraph, B. D. Hubbard, chief operator in the general offices of the New Haven road, and Michael Kelly, district repairman, stationed at Stamford, Conn., in charge of all repairs in the electric zone for the Western Union Telegraph Company. Mr. Hubbard being constantly stationed at the end of the telegraph lines that pass through the electric zone, Mr. Kelly being in charge of such repairs as were required to these lines, and Mr. Smith being in general charge of telegraph operation, it occurred to me that a general conference would develop the difficulties experienced and the methods pursued to rectify the troubles—all of which would throw light on the actual results obtained since the electrification zone between Stamford and Woodlawn has been considered as completed.

The memorandum of categorical questions I asked at this conference is as follows:

Question. How many telegraph lines are you operating in the electric zone?

Answer. Ten railroad lines, seven Western Union, and three spares.

Q. Would these lines be operative without the use of compensating transformers?

A. No.

Q. By reason of the induction present have you ever had any burnouts on these lines?

A. Not since full commercial railway service has been in operation. (Mr. Kelly, however, offered an interesting commentary at this junction. He explained that upon one occasion during the early part of preliminary operation the continuity of the track was broken as a return circuit to the power house by inserting insulating joints at three places. This break caused a rise of voltage and consequent increase of current in one of the compensating transformers, and resulted in the burning out of the transformers. Upon another occasion the telegraph line was crossed with the high-tension railroad circuit, with the attendant result of burning out another compensating transformer. Except for these two cases in the preliminary stage of operation, it seems that no compensating transformers have been lost.)

Q. Are there ever times when by reason of induction any of the lines became inoperative?

(In answer to this question Mr. Hubbard explained that at times, principally during the morning and afternoon—the periods of heavy traction load—the buzzing on one of the through lines between New York and Boston was so severe as to be just outside the limit of adjustment of the instrument, and for a minute or two it would be necessary for the operators to cease communicating. This particular line is known as 72. It developed, however, that this wire from Bridgeport to Boston has an iron circuit, while the other lines from New York to Boston are of copper throughout. I have suggested the use of a copper wire from Bridgeport to Boston, thus increasing the conductivity of 72, which will cut down the ratio of induction to working current. In the event of this rectifying the trouble, it may then be said that at no time will any of the twenty wires in the electric zone be inoperative, due to induction. It is fair also to add that Mr. Hubbard explained the excessive buzzing described on 72, as quite exceptional.)

Q. Has the Western Union Company made any complaints concerning the ten wires which lead from our electric zone to their New York office?

A. No complaints in the last year, beyond ordinary telegraphic troubles.

Q. Are there any complaints made about the wires by the operators in the general offices of the New Haven road?

A. None.

Q. What is the extra maintenance required by reason of the addition of the compensating transformers on your telegraph lines in the electric zone?

A. There are more fuse blow-outs, escapes, and grounds.

Q. Are these troubles so numerous as to affect the efficiency of telegraphic transmission?

A. There have been no complaints in regard to the availability of the lines for service. These new occurrences simply require an extra inspection, which was not required under the old conditions.

Q. Under what conditions do you experience these troubles?

A. The failure of an insulator on the catenary system is generally the cause of a telegraph fuse blow-out, the starting of an escape, or a ground. (This effect is pointed out on the first page of Mr. Taylor's paper.)

Q. How often do you inspect the compensating transformers?

A. Each transformer is inspected about twice a month.

Q. Do fuse blow-outs, escapes, and grounds occur in any one particular point on the electric zone?

A. Yes, at Portchester, for example, where telegraph lines run more closely to the high-tension wires than at any other part of the zone.

It is fair to say that the index of efficiency in telegraphic service is the number and reliability of messages per unit of time. Likewise in railroading its index is the number of locomotive-miles per engine failure. Our records for the month of July 1909, show that the electric locomotive mileage was 14,000 miles per engine failure, while for steam the figure was 6238 miles per engine failure. Thus the steam record was less than 45 per cent as good as the electric.

In conclusion the writer cannot refrain from pointing to the two kinds of trouble—surmountable and insurmountable. The New Haven electrification, in turning out trouble to its friends, the telegraph and telephone, was not selfish and did not forget to lay a few eggs in its own nest. Some of these were hatched, but I am glad to be able to add that this class of offspring lived only long enough to make a record of its birth. While the first installation of the single-phase system as arranged on the New Haven road produces maximum induction, it is not uninteresting to note that as extensions of this system take place, by reason of power stations delivering current that virtually divides itself in equal amounts and in opposite directions along the righ-of-way, the inductive effects will tend to eliminate themselves, and the future will be more free from them than the present.

Charles P. Steinmetz. I consider Mr. Taylor's paper as particularly inportant because it is a complete and explicit exposition of the relations between the two classes of electrical transmission—the transmission of power and the transmission of intelligence.

We know that electric power circuits may, and occasionally do interfere with their weaker brothers, the telegraph and the telephone systems. The problem before us now—which is not a problem of interest only to the power engineer or the railway man or the telegraph engineer, but one of great importance to the electrical engineering industry at large—cannot be solved by saying that we are power engineers and expect the telegraph and telephone systems to take care of themselves. This would be as unfair and as untenable as it would be for the telegraph or telephone engineers to say: we were the first ones in the field and must not be interfered with, and we insist that the electric power systems shall be installed in such a manner as not to interfere with us. As stated by President Stillwell, the latter short-sighted policy has been manifested by the American Water Works Association.

Mr. Taylor's paper shows us that from the engineering point of view neither of these policies is tenable, and that the question can only be solved by coöperation between these two classes of engineers. The power engineer must make some concessions in the arrangement of his system to reduce interference, and the telegraph and telephone engineer must be willing to go to some inconvenience to protect his system against interference which cannot be avoided by the power engineer. It behooves us power engineers to give consideration to our weaker brothers, the telegraph and telephone systems, who are being interfered with by our circuits and who cannot interfere with us; for while we are to-day the stronger, sometime we may be the weaker, and then ready to cry out for protection when powerful ether waves from nearby wireless telegraph stations cause trouble in our low-voltage lighting circuits.

While with the advance of the electrical industry we are obliged to specialize more and more, at the same time this advance brings us closer together and makes us more and more dependent upon each other, obliges us more to consider the interests of others and not simply our own particular field. Mr. Taylor's paper is, therefore, of extreme interest not only to the telephone and telegraph engineer, but also to the power engineer, by drawing attention to these interferences and showing how they originate, or what character they are, and indicating in general the arrangements which may be used to mitigate or obviate them. Obviously, the paper can be only a broad outline, since it is the first paper on the mutual relation between the telegraph and the telephone on one side and electric power on the other side. It is therefore regrettable that the telegraph and telephone engineers could not be induced to discuss the subject here and to give us the benefit of their ideas.

Coming to a more specific discussion of the paper, Fig. 14 shows a diagram of an arc circuit which goes out on one street and comes back on another street in another part of town, looping a city block or an entire city district. Such loops of overhead alternating arc wires are extremely bad for the telephone and telegraph circuits, but fortunately they are going more and more out of use.

I cannot agree with Mr. Taylor's explanation of the greater frequency of grounds on arc circuits as being due to the higher voltage. It appears to me that the fact that arc circuits are more liable to faults and grounds than primary distribution circuits is due to the nature of their load. The arc circuit feeds directly into the consuming devices—arc lamps. The primary distribution circuit feeds only into transforming devices - transformers which are relatively small in number and can be very well insulated—while the arc lamp cannot be insulated to stand the voltage between the arc circuit and the ground and therefore must remain a part of the arc circuit, is to be considered as alive, and leads to a greater liability of trouble from grounds and faults by contact with trees, etc. This condition is aggravated by the limitations in the location of arc circuits, which cannot choose their path, but must run wherever arc lamps are desired, even if they have to go through trees, etc. The primary distribution circuit has a greater choice of its path in choosing the location of the transformer so as to give the least chance to interference. The result is that the arc circuit is always much more liable to grounds. Incidentally, a ground in an arc circuit is very much less troublesome, because current and power are limited. For this very reason it has become almost the general custom where arcs are operated from alternating-current systems to separate the arc circuit by a transformer from the primary distribution system; that is, to use constant-current transformers instead of the cheaper constant-current reactances.

I do not quite agree with Mr. Taylor on the improbability of trouble from the third harmonic of the generator wave, for the reason that my first introduction to the third harmonic took place ten or twelve years ago when we grounded the generator neutral in the Mechanicsville–Schenectady transmission. The telephone line on the same poles was put out of service entirely, and we were obliged to take off the ground—and then the telephone line operated again. Undoubtedly by a proper arrangement of telephone wires and power wires, as described in Mr. Taylor's paper, operation could have been made satisfactory; nevertheless, as it was installed, the telephone circuit was satisfactory with an ungrounded neutral and was not satisfactory with a grounded neutral. At that time we took an oscillogram of the neutral current and found the third harmonic very greatly distorted by the ninth harmonic. Since the frequency was 40 cycles, the ninth harmonic, of 540 cycles, was fairly close to the maximum sensitivity of the ear. This illustrates what Mr. Taylor has said, that one may expect more trouble from the higher harmonics of the generator, since these higher harmonics have a greater physiological equivalent in the ear than has the fundamental.

Regarding the image conductor, its meaning is frequently misunderstood. The image conductor; that is, the image below the ground, of the trolley wire, does not mean that the center of the return current is in it. It means: if we assume that the ground is a perfect conductor and that the return current therefore does not penetrate at all below the ground, but flows entirely at the surface of the ground, as a current sheet, then the inductance of the trolley wire against this current sheet at the surface of the ground would be the same as the inductance of the trolley wire against the image conductor. As the ground is not a perfect conductor, the current does not flow at the surface but flows at least partly some distance below the surface; as a result thereof the inductance of the trolley is not that of the trolley wire against the image conductor but is greater, corresponding to an image conductor deeper below the ground, as was mentioned by Mr. Copley as a result of the tests on the New Haven system. Especially in a steam railroad system, where the road-bed and the soil near the surface are probably of relatively high resistance, the current returns, not at the very surface but at a considerable distance below it. This means that the equivalent return conductor, that conductor below the ground which would give the same self-inductance to the trolley wire, would be very much deeper than the image conductor. The image conductor must not be mistaken for the center of the return current; it is a representation of the current sheet at the surface.

The great difficulty with the theoretical investigation of these disturbances is the complexity of the circuits for which we have to calculate the mutual inductance and the mutual capacity, and here we find that the greatest trouble is in the calculation of the mutual capacity. Regarding the mutual inductance, some uncertainty may exist in the location of the return circuit as to whether it is close to the surface or deeper in the ground, but the difference in the numerical value produced thereby is not very great. In his conception of the lines of magnetic force, Farady has given us such a beautiful illustration of the magnetic field that we can see it and calculate the magnetic inductance mathematically while knowing exactly what we are doing. This induces confidence in our results. Unfortunately, in the field of electrostatics our mathematical theories are still those of the early dawn of electrical science; we are still dealing with conceptions as they were developed in those days, before the law of conservation of energy, when heat, electricity and magnetism were "imponderables", forms of matter without weight. We speak of such non-existing things as the electrostatic charge of a conductor, the surface density of the electrostatic charge, and discuss the static self-potential of the conductor There is no such thing as an electrostatic charge of a conductor. Since Faraday's time, in the field of magnetism we do not speak of the magnetic charge of a magnet, but in electrostatics we still have the antiquated conception of an electric charge, instead of considering the effect as an electrostatic field in space. What is necessary now is that some Faraday give us as clear a conception of the electrostatic field as we have of the electromagnetic field, so that we can deal with the lines of electrostatic force, not with the antiquated conception of electrostatic charges which are suitable for mathematical formulas, but in which we cannot see physically the meaning of the mathematical representation; for, so long as we cannot see the physical meaning, we can have no confidence in the correctness of the methods we are using.

Unfortunately at present the probability of the reduction of the conceptions of electrostatic phenomena to the same simplicity and obviousness, if I may so term it, as that of electromagnetic phenomena is unlikely, since most of the investigators have been carried away by the prevailing fad of representing the phenomena of electric power flow, not as Faraday and Maxwell did, as conditions of stress in the space—as an electric field—but as due to the migration of some form of dematerialized matter, the electrons, between the molecules of matter. Before we can get a clearer conception it will be necessary for some genius to take up this electronic theory and separate the mass of chaff from the few grains of truth, and so make the ionic theory a useful instrument of research instead of a stumbling block to the advance of exact science, as it is beginning to be at present. Then we will have the electrostatic field as tangible as the electromagnetic field is now.

At present, when dealing with electrostatic phenomena, such as the mutual capacity of circuits, the only way I can find that is at all satisfactory and not liable to confuse one, is not to calculate the electrostatic capacities at all, but to calculate the electromagnetic inductance and get the capacity from the inductance by the relation existing between the two by means of the velocity of light. The product of capacity and inductance equals the square of the length divided by the square of the velocity of light. Thus we get the capacity, mutual as well as self-capacity, from the inductance of the circuits, and do not need to consider particular methods of calculating capacities. In calculating capacities from inductance by the velocity of light, the error is that the actual electric velocity is slower than that of light, due to the energy loss in the electric circuit, which retards the velocity. If, however, as inductance we do not use the total inductance of the conductor, but only the external inductance—the logarithmic part—then we eliminate the effect due to the energy loss and get the exact value of the capacity.

L. C. Nicholson (by letter): The author points out the slight cause for transposing a three-phase power line, unless telephone or telegraph lines are near enough to be affected, and in general advises against transpositions for the average case. He does not advise us how near is "near enough", however, and the general conception is that the farther away a telephone line is from a high-tension transmission line the better. To a certain extent this is true, but the limiting distance is not necessarily that determined by inductive effects which could be offset by transpositions, but rather it is that distance which we may call "respectful", which is determined by mechanical considerations, such as liability to accidental contact due to breakage of wires or other similar causes. We wish to cite a concrete case resulting from several years' operation of high-tension, high-power lines in close proximity to parallel telegraph and telephone lines, and to note the negligible inductive and static effects with and without transpositions in the power circuits.

The three-phase, 60,000-volt, 25-cycle transmission lines of the Niagara, Lockport & Ontario Power Company from Niagara Falls to Syracuse run parallel and closely adjacent to the same company's private telephone lines for a distance of 200 miles, and to Western Union telegraph and telephone circuits for 125 miles. The separation between the power lines and the private telephone line varies from 150 ft. to 10 ft., the average distance being about 50 ft., and between the power lines and Western Union lines the average distance is about 70 ft., though frequently not more than 30 ft.

The power lines are transposed only where they are parallel to the Western Union circuits in a manner mentioned below. The private telephone line is a copper circuit on separate poles on the power line right-of-way. The wires are transposed ten times per mile. The Western Union circuits consist of one continuous two-wire telephone circuit transposed twice per mile, and eighteen telegraph ground-return circuits using from 70 to 250 volts storage-battery current.

Originally, and before voltage was put on the power line paralleling the Western Union circuits, transpositions were carefully put in to prevent inductive effects. In a distance of 105 miles, thirty 120-degree transpositions, or ten total transpositions were placed at intervals varying from 3 to 5 miles. The distance between consecutive transposition points was calculated separately for each case from the average separation between the power and telegraph lines, using as a basis one 120-degree transposition every 4 miles for 80 ft. separation between circuits.

After more than a year's operation of this line transmitting some 6000 h.p., during which time no disturbance of any kind arising from normal operation was felt on the adjacent telephone or telegraph lines, eighteen of the thirty transpositions were changed so that the upper conductor was no longer transposed, but remained the upper conductor for a distance of 57 miles. The two lower conductors were transposed 180 degrees at the original transposition points. The remaining twelve 120-degree transpositions covering 48 miles were unchanged. Evidently the 180-degree transposition scheme gives a circuit equivalent to a non-transposed single-phase circuit, the two conductors of which are in a vertical plane with, in this case, 6 ft. separation. During two years' operation of this line with loads as high as 15,000 h.p. no disturbance has been felt on adjacent parallel telephone and telegraph circuits during normal operation. In view of this experience, transpositions of the power wires is considered entirely unnecessary, and in subsequent lines which have been built contiguous to foreign circuits no transpositions have been made.

As stated above, neither the private telephone system nor the Western Union telephone or telegraph circuits can detect the presence of the power circuits when operating normally. However, when a ground occurs on one phase of the power line the electrostatic unbalancing causes chattering of telegraph instruments and sometimes blows fuses in the telegraph or telephone circuits. These disturbances are always of short duration, being usually less than 20 sec., which is the maximum time a ground can remain on any part of the system before being automatically cut off. Electromagnetic effects of a ground are felt only slightly on account of a high resistance placed in the neutral connection to earth of the sending transformers, which allows the passage of approximately 30 amperes earth current. Formerly when the system was operated with a thoroughly grounded neutral, the electromagnetic effects were considerable on account of short-circuit currents to earth, sometimes burning out fuses, relays, and lightning arresters.

Short-circuits between wires do not ordinarily cause inductive disturbances, since when they occur they are nearly always confined to a single location and do not involve the earth as a conductor.

Other forms of abnormal operations have been experienced and their effects upon parallel circuits noted. Single-phase power transmitted over two wires of a three-phase line causes no disturbance.

The combination of transmitting three-phase power approximately one-half the total distance and single-phase power the remaining distance, after the manner shown in *B*, Fig. 15, has never caused any inductive disturbance of any kind.

Transmitting power three-phase over duplicate lines separated from each other several miles, using two conductors of one line and one conductor of the other line to make up a single three-phase circuit, causes disturbances which appear to be due entirely to electromagnetic induction. Thus, normal voltage on only one wire of either line causes no trouble unless considerable three-phase load is delivered—using two wires of the other line—showing that the purely electrostatic effect is negligible under conditions of normal voltage. When, however, a ground occurs on one phase, causing full line-potential to exist between the other two phases to ground, the electrostatic effect shows up in a mild form, as mentioned above.

In general, experience shows that with separation between power and telephone lines as mentioned above, transposition of power wires is unnecessary; that transient electrostatic and electromagnetic effects accompanying grounds on the power line are mild and of slight consequence; that the only class of disturbances that will cause trouble to telephone or telegraph instruments is caused by heavy electromagnetic effects induced by short-circuit currents passing through the earth for considerable distances, as may occur in star-connected, high-power, high-voltage systems which operate with a grounded neutral.

J. C. Barclay (by letter): Mr. Murray has made an assertion to the effect that there is no interference with the telegraph service due to the operation of the single-phase system on the New York, New Haven & Hartford Railroad. This is far from being correct. It is true that by means of the neutralizing transformers interposed in the telegraph circuits at two-mile intervals along the electrified zone, the working of the wires has been rendered more or less feasible, where otherwise complete demoralization of the service would have undoubtedly resulted from the disturbances induced therein; but the impression sought to be conveyed that these transformers have proved a panacea for all the inductive ills to which the wires are subjected, is not at all justified by the facts in the case.

There are various reasons why the neutralizing apparatus is not entirely effective under the present conditions of installation. In the first place, escaping currents from direct-current trolley systems find access to the primary windings of the transformers, the cores of which become magnetized, and diminish the degree of neutralization that might otherwise be secured. The working currents of the telegraph circuits in passing through the secondary windings also excite in the transformer cores an amount of magnetism that varies in proportion to the number of telegraph keys that happen to be open or closed, with corresponding variations in the neutralizing values. And, on account of phase-distortion, the counteracting electromotive forces developed by the action of the transformers are not directed in a manner to bring about complete nullification, even though the magnitude of the nullifying forces could be made equal to that of the disturbing forces.

As a result of such conditions, residual voltages and currents of varying intensity are ever present in the telegraph wires, the detrimental effects of which depend, more or less, upon the length and character of the circuit, and the strength of the working current; but are mostly manifest under unfavorable climatic conditions when the sensibility of the receiving apparatus to such currents is at a maximum.

Tests have shown that these residual or superposed electromotive forces in the wires possess an average pressure of about 15 volts even under normal operating conditions, and although the legibility of the received signals on the regular Morse apparatus may not, as a rule, be perceptibly impaired thereby, there is, nevertheless, a marked depreciation in their character or quality that tends materially to affect the efficiency of the service; for, to quote Mr. Taylor in the paper above alluded to:

> Disturbances on the line which do not actually upset the working, may make considerable difference in the comfort or state of mind in which the operator does his work.

From what has been said with regard to the effects observed on the comparatively insensible Morse apparatus, it naturally follows that the more delicate instruments employed in high-speed and multiplex systems feel more acutely the influence of the disquieting currents; and it may be stated as a matter of fact that such systems can only be operated over wires extending through the electrified zone at a considerable sacrifice of speed and efficiency under the most favorable conditions, and not at all under abnormal conditions of working.

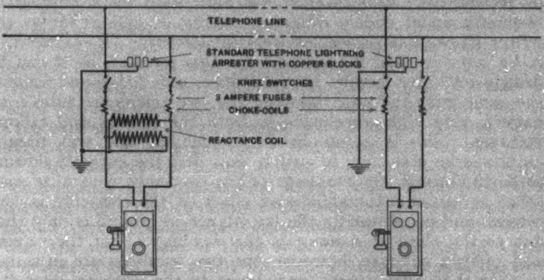
There is no disposition on the part of the writer to be hypercritical in regard to this matter, but as the result of practical experience the fact cannot be too strongly stated and emphasized—that the costly and cumbersome transforming devices, which, in addition to other disadvantages, necessitated the sacrifice of three copper wires to provide a neutralizing circuit, as well as the complete transposition of all the telegraph wires at each of the ten transforming stations along the affected zone, have not brought about a condition in the working of the wires that can in any way be regarded as satisfactory from a telegraph point of view.

A. L. Cook (by letter): In considering the protection of telephone lines for high-tension transmission line service, Mr. Taylor describes an insulating transformer that has been developed to enable a telephone system to be safely used even when a considerable difference of potential exists between the telephone line and ground. The apparatus he describes would undoubtedly protect the user of the telephone, but there are a number of objections to its use. Where there are a large number of telephone stations installed on a long line, it is generally necessary to ring all of the bells simultaneously when calling one of the stations. In this case a considerable amount of current must be transmitted through the transformer at the ringing station and supplied to the transformer at the other stations. In addition to the current actually required for ringing the bells, the magneto-generator must supply the magnetizing current for all the transformers on the line; and while this may be small for a single transformer, with a large number of stations the current required for this purpose would certainly impair the ringing qualities of the line. When talking over the line the voice currents also suffer this same double transformation, and even with the best design possible there is sure to be a noticeable effect on the talking qualities. Unfortunately, the best design of a transformer for ringing service is not the best for talking, consequently any commercial design must be a compromise between these two conflicting requirements. Tests of the particular type of transformer illustrated by Mr. Taylor indicate that the use of one of these transformers affects the talking qualities of a line to about the same extent as would the introduction of five miles of ordinary No. 19 dry paper-insulated telephone cable.

The equipment described is also relatively expensive in first cost, since the cost of the protective apparatus illustrated is more than double that of a good magneto telephone instrument of the type commonly used in this class of work. The principal objection to Mr. Taylor's arrangement is, however, that it does not eliminate the dangerous potential from the telephone system, and for this reason it is only safe to use the line at points where the protective apparatus is installed. It would, therefore, be dangerous for a patrolman to attach a portable telephone set at any point on the line unless he carried around with him the full protective equipment illustrated, which is out of the question because of its size and weight. If patrol stations are located along the line with this protective apparatus installed therein, the telephone system would be very expensive. There is also the objection that with the existence of a high voltage on the telephone line, it becomes more difficult to maintain the system in a satisfactory working condition. If the power wires are not transposed, a high voltage will exist on the telephone line even under normal conditions, and there would be more trouble from leaks on the line, causing a noisy circuit. Even the use of better insulation is only a partial remedy, as the existence of the high voltage would tend to increase the chance of leaks developing. If the power wires are transposed there would normally be no appreciable voltage on the telephone line; but in the event of a ground on a power wire there would be a a very high potential induced, and the insulation of the telephone system might break down at just the time when such a failure would be most serious in its consequences.

The writer believes it is generally better to prevent any possibility of there being a high potential between the telephone line and ground, rather than to attempt to use for purposes of communication what is virtually a high-tension line, so far as danger to life is concerned. The voltage induced on the telephone line may be eliminated by grounding the two wires through reactances or resistances. This method has been used by a number of engineers under widely different conditions, and as far as the writer knows has proved entirely satisfactory. A reactance is more suitable than a resistance for this purpose, as it can be designed to give a very low-resistance path to ground while at the same time the path between the two telephone wires may have a very high impedance to both the ringing and talking voltages. This is accomplished by winding the two circuits on the same iron core, in such a way that the currents flowing to earth through the windings of the reactance neutralize each other as far as any magnetizing effect on the iron core is concerned, and consequently the impedance to ground is only that due to the ohmic resistance of the windings. For the ringing and talking voltages, however, the two windings are in series, so that they offer a high impedance to the working currents; and since these are not subjected to any transformations by the protective apparatus, the maximum efficiency of the line is obtained. In addition to the reactance coils, it is, of course, necessary to provide discharge gaps, set to break down at a low voltage, so that in the event of an accident to the protective coils the telephone line will be grounded and thus rendered safe. With a proper equipment of this character, a patrolman can safely tap the telephone line at any point and communicate with the station, using an ordinary portable set for the purpose. The cost of this type of protection is also considerably less than that described by the author, particularly where there are a large number of stations on the line.

The writer had occasion a few years ago to devise a protective system for a telephone line operated in connection with a 65-mile, 44,000-volt, three-phase transmission system. This was a single line with the telephone wires carried on the same poles, about 5 ft. below the bottom power wires. The power wires are given a complete transposition between successive load points and the telephone line is transposed at every sixth pole. The system operates without a grounded neutral. Under normal conditions there is no measurable voltage between the telephone line and ground, and the talking qualities of the line are very satisfactory. Measurements were made with one of the power wires grounded, using a voltmeter and potential transformer, and it was found that at normal line voltage, under these conditions, there would be a difference of potential of about 10,000 volts between the telephone wires and ground. An ammeter connected between the two telephone wires and ground showed that there were about 5 amperes flowing. Suitable reactance coils and protective apparatus, arranged as shown in Fig. 1, were installed at two points on the line, and the same tests repeated. It was then found that with normal voltage on the line, and one of the power wires grounded, the voltage on the telephone line was only 14 volts. The telephones could be used very satisfactorily under these conditions, and there was no evidence of any disturbing earth currents flowing between the two reactance coils.



ARRANGEMENT AT STATIONS HAVING REACTANCE COIL

ARRANGEMENT AT OTHER STATIONS

Fig. 1

A. W. Copley (by letter): The question brought up by Mr. Taylor as to whether the self-induction of a circuit consisting of a trolley wire with a wire return would be greater than with rail and earth return, is easily settled. A circuit made up of a 4/0 trolley wire with 100-lb. rail return has constants as follows for a 25-cycle, single-track road:

* Resistance volts for 100 amperes per mile,

Trolley	26
Rail	3
Total	29

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* PROCEEDINGS A. I. E. E., December, 1908, p. 1733.

Reactance volts per 100 amperes per mile,	
Trolley wire (internal)	1.3
Rails	1.5
Due to field between trolley wire, and return circuit	44.2
Total	47
Impedance—total	55.3

In order to obtain the same reactance with wire return the trolley and return wire must be separated by a distance x determined by the formula:

Reactance volts per mile per 100 amperes $= 5.28 \times 1.92 \log x/0.78$ radius of wire.

This formula holds true when the return wire is of the same size as the trolley wire. It includes not only the reactance due to the field between the wires but also that due to the field inside the wires, hence it represents the total reactance of the circuit.

The radius of the 4/0 wire is 0.20 ft. On placing the reactance equal to 47, and solving the equation for x, the result is 1.6 ft. In other words, the reactance of a circuit consisting of the trolley wire and a return wire at a distance of 1.6 ft. is 47 volts per mile, which is equal to the reactance of the normal circuit consisting of the trolley wire and the ordinary track return.

It is obvious that a greater separation between the wires would cause an increased reactance, consequently Mr. Scott is correct in asserting that a separation of 2 ft. between the wires would cause a greater reactance than that of the normal circuit with track return.

It may be further noted that the resistance drop for the circuit with the 4/0 return is 52 volts per 100 amperes per mile, instead of 29 volts with the normal conditions using the track return. It follows, therefore, that the overhead return circuit will probably involve increased inductance, increased cost of copper, and an increased resistance loss, unless a very large amount of copper is installed.

The reason that the reactances of the trolley-track circuit is low is on account of the large effective diameter of the return circuit. The radius of the conductor does not enter, however, into the formula for obtaining the voltage induced in an entirely separate circuit, such as a telegraph line and its return, this voltage being proportional to the logarithm of the ratio of the distances from the telegraph line of the trolley and its return circuit. Hence the voltage induced in the telegraph circuit is dependent upon the effective depth of the current in the earth.

Frank F. Fowle (by letter): It has long been clearly understood that an electric circuit transmits energy, not through the body of its conductors, except to an almost negligible extent, but through the dielectric surrounding the circuit. The conductors are but a guide for the energy in its course of transmission through the dielectric. The extent of surrounding dielectric which is energized is also known to depend upon the geometric disposition of the conductors in a plane perpendicular to the circuit. The more widely the conductors are separated, in this plane—voltage, power, and frequency remaining constant—the more extensive becomes the body of energized dielectric.

Theoretically the dielectric is energized, in a direction transverse to the circuit, to an infinite distance; but the dielectric stresses diminish at increasing distances from the circuit in a much faster ratio than the distance. The respective intensities of the electric and magnetic fields are expressed, for any given point, by logarithmic functions of the distances from the point to the wires of the circuit, in a perpendicular plane. When the point is at a great distance from the circuit compared with the distances between the conductors composing the circuit, the field intensities become very small and diminish indefinitely as the point moves away from the circuit.

The phenomenon of induction occurs when a second circuit is placed in parallel relation with the energized circuit, at such a perpendicular distance from it that the field intensities have appreciable values. The second circuit will then have upon it electromagnetically induced electromotive forces and electrostatically induced charges. The second circuit will absorb a portion of the energy of the first circuit, derived from the dielectric through which it is transmitted.

By reason of the fact that telephone and telegraph systems operate with low voltage and low power, with sensitive apparatus, they are exceedingly subject to interferences from systems of high voltage and high power. The phenomenon of induction between such systems is, it is true, a mutual one, and telephone and telegraph systems induce disturbances in power systems. But the disturbance to the latter is infinitesimal, for two reasons: first, the initial energy in telephone and telegraph systems is relatively weak of itself; and, secondly, the extremely weak induction in the power circuit virtually vanishes in comparison with the initial energy in the power system.

When telephone and telegraph systems exist in parallel proximity to high-voltage, high-power systems, then there is usually interference with the telephone and telegraph systems. This interference varies in degree with the distance between the systems, with the voltage, current, and frequency of the power system, with the geometrical configuration of the power circuit, with the presence of harmonics in the voltage wave and the current wave in the power circuit, with the existence of normal or abnormal grounds on the power system or on the telephone system, with the use of metallic or ground return circuits in the telephone and telegraph systems, and with the system of transposition employed in any or all of the systems.

The problems or difficulties which such a situation presents have two aspects; one of these is the legal aspect and the other is the technical or engineering aspect. Both are of great interest to the engineer. The legal problem, stripped of all details, appears to be one of ownership or right of use of the ether. When a telephone system parallels a power system at a distance of, say, 50 ft. and both systems hold secure legal titles to separate, out adjoining, physical rights-of-way, the inquiry is whether the power system is trespassing in a legal sense, when some of its energy is transmitted through the space over the telephone right-of-way, to the damage and impairment of the operation of the telephone system. Certainly it cannot be held that any one interest or group of interests is entitled to the exclusive use of all the ether. The public requires both transportation and communication, and therefore the public interest requires that this problem be so solved as to harmonize the conflicting interests to the greatest possible degree, without distributing the burden unfairly on either. In the general sense this situation closely resembles the electrolysis problem, where the interests of the street railways and those of municipalities or private companies operating water works are in conflict as to the right of the railway companies to utilize the earth as a return conductor. In the latter case it is undoubtedly a complete preventive of damage to require the railways to use the double-trolley system; and so also it is in the case of the alternating-current systems of traction as regards their disturbance of telephone and telegraph systems. But from the railway point of view a cure so drastic seems unreasonable and burdensome. It remains for engineers to work out, if possible, a solution that will more completely harmonize these opposite interests.

The problem before the engineer naturally divides itself into two lines of investigation, one relating to means of prevention and the other to means of restriction. Mr. Taylor's paper deals with both of these. The means of prevention apply naturally to the railway system, while those of restriction apply to telephone and telegraph systems. Prevention, rather than restriction, is greatly to be desired, if feasible and economical. Fig. 19 and 20 of the paper bring out very clearly some of the means of partial prevention.

The value of a ground-wire, as a means of diminishing the spread of the electrostatic field, is quite important. The following case has come to the writer's attention. A single-phase traction system operating at 3300 volts and 25 cycles, carried on the trolley pole-line a 33,000-volt, 25-cycle, three-phase transmission, a metallic telephone circuit, and a ground-wire erected for the protection of the transmission line from lightning. When the system was put into operation the ground-wire had not been provided with earth connections. It was found that the induced potentials on the telephone line were extremely troublesome and dangerous. But after the ground-wire had been earthed every few poles, the troubles with the telephone line disappeared in large measure, and it became possible to use it, whereas it had been practically impossible before. Of course a potential-neutralizing conductor would theoretically be even better, but it could not then serve the further purpose of a lightning guard.

The writer afterward made a series of observations of the induced potentials in a telephone system, parallel to the traction system just mentioned. He found that the potentials appeared simultaneously with the passage of trains over the traction line, and observed also that there was no potential when there were no trains on the line or when the trains were at standstill. If there had been any electrostatic induction of appreciable magnitude, the observed potential could not have been zero in the absence of trains on the line. These observed potentials were also of a widely fluctuating character, and corresponded generally with the fluctuations of trolley current. There were three trolley sections fed from two sub-stations, the middle section being fed from both ends, and it was observed that the position of the train was a factor in the magnitude of the induced potential. The last mentioned factor was difficult of analysis owing to the varying distance between the traction line and the telephone line.

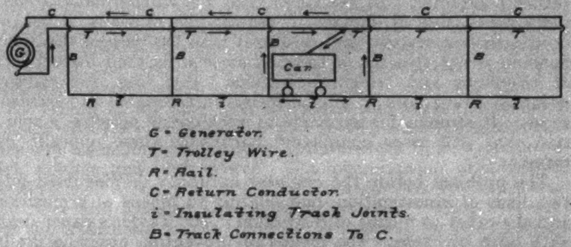


FIG. 1

The electromagnetic field will be greatly restricted by means of a current-neutralizing conductor, as Mr. Taylor says. It is fundamentally necessary for maximum efficiency that the neutralizing conductor be as close to the trolley wire as feasible, and that it carry a current equal to the trolley current in magnitude, but 180 degrees out of phase with it. The writer proposed such a conductor some years ago and endeavored, but unsuccessfully, to have it tried out on a small single-phase road, in 1906.

The features of this arrangement appear in Fig. 1 and 2. The return conductor in this arrangement fulfils largely the functions of a ground-wire as well. The use of sectional track insulators, or insulating rail joints, is proposed in order to diminish the flow of current in the track further than otherwise would occur; the track sections can very conveniently be made to correspond with the lengths of signal blocks, if automatic signals are desired. In the latter case the overhead conductor would be connected to the middle of an inductive track bond, which would be connected in turn between the rails; or only one rail might be used for the propulsion current, reserving the other for signaling purposes.

On account of the impedance drop in the return conductor, there would be some leakage to earth from the rails. The arrangement shown in Fig. 1 is therefore not perfect. Series transformers may be employed to remedy this defect, as shown in Fig. 3. These transformers are arranged with their primaries in series with the trolley wire and their secondaries in series with the return conductor.

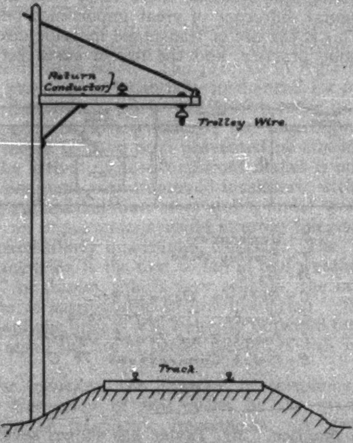


FIG. 2

I cannot agree with Mr. Taylor's statement that these transformers should have a 1:1 ratio. The ratio must be such that with currents of equal magnitude in primary and secondary, but 180 degrees out of phase, the secondary induced electromotive force will just overcome the impedance drop in the return circuit, or such portion of it as corresponds to the section in which the transformer is situated. The ratio will depend, therefore, upon the impedance of the return conductor. The magnitude and phase of the secondary terminal electromotive force may be regulated by means of shunts on the primary or the secondary, or both; and by variation of the primary or secondary turns, and by the latter in combination with the shunts before mentioned.

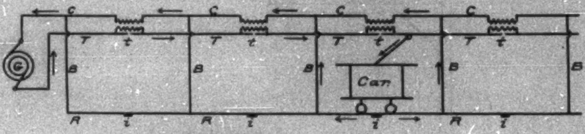
The means of prevention, as applied to single-phase traction systems, may be summed up as follows:

1. One or more overhead conductors for the purpose of neutralizing or restricting the electromagnetic and electrostatic fields.

2. Means for limiting the flow of current in the track to short sections.

3. Means for maintaining the entire track at zero or earth potential as nearly as possible.

Turning now to means of restriction as applied to the telephone and telegraph systems, there must first be recognized one fundamental difference of great importance between these systems. This is the use of transposed metallic circuits in (the best) telephone practice, and the use of earth return circuits in telegraph practice. Mr. Taylor has shown several metallic circuit schemes for telegraph transmission, but none of these is in general use in this country. Telegraph systems suffer from induction in a far worse degree than telephone systems, because of the use of the earth return. But to require the telegraph companies to convert their systems over to metallic working would be, from their viewpoint, a much more drastic remedy than to compel the traction companies to use the double trolley. The change from grounded working to metallic working in a telegraph line would halve the number of physical circuits and double the investment per circuit mile. The effect which this would have upon rates is obvious; and the final result of such a considerable increase of rates would be a material loss of business, and public inconvenience.



G - Generator.
T - Trolley Wire.
R - Rail.
C - Return Conductor.
t - Booster Transformers.
i - Insulating Track Joints.
B - Track Connections To C.

FIG. 3

All telephone and telegraph circuits are separable into two divisions, one overhead and one underground. The overhead circuit is, for the great part, bare copper and iron wire, carried on pony glass insulators of relatively poor insulating qualities when dirty and wet. The leakage resistance of such circuits varies excessively with the weather. The underground circuit is in cable and possesses properties which remain substantially constant. This difference renders the overhead circuit the most difficult one to remedy.

Circuits in cable have been quite successfully treated in a few instances, by means of compensating transformers. Such circuits are not subject to electrostatic induction because of the enveloping metal sheath, which acts as a shield or electrostatic screen. The magnetic field, however, penetrates this sheath and gives serious trouble.

On overhead bare wire circuits the compensating transformers do not meet all the changing conditions with respect to leakage, but still afford some relief. The practice in regard to line insulators has remained substantially unchanged for many years. The form of insulator in use is well known to be no more than adequate as regards surface leakage, but any improvement in this respect seems to have been prevented by considerations of expense. The arrival of new conditions makes it now very desirable to experiment with improved insulators, with the object of making the line insulation more stable under weather variations. Such an improvement would improve telegraph working in general, particularly quadruplex working. The "common" side of a quadruplex is the first to fail in bad weather, whereas the "polar" or duplex side is very reliable; the failure of the common side is attributable to low insulation. The working of loaded telephone lines is also seriously impaired by low insulation. Here again the use of better insulators will improve the service.

Mr. Taylor mentions the practice of telephone companies in using a frequency of 800 cycles as the average of the general range of telephonic frequencies. A general figure of 750 cycles has been used considerably, because this value gave fair agreement between the results of speech transmission tests over actual lines and the results of calculation from theory. A complete theoretical investigation cannot be made by the use, however, of a single frequency. For practical purposes a range from 100 cycles to 2500 cycles is quite satisfactory, using steps of 100 to 200 cycles.

The point made by Mr. Taylor in reference to the need for more careful attention to electrical balance in telephone instruments and apparatus is very well taken. The necessity for high insulation can be added to this.

I cannot agree with Mr. Taylor's conclusion that grounding the neutral of a three-phase system at one or more places is not of material consequence. The effect of this depends upon the existence of a triple-frequency harmonic in the voltage wave;

where this is not present there will be no change of consequence in the induced disturbance in parallel systems. But where it is present there will be a serious increase, due to the fact that the resultant vector of three such harmonics is a single wave which tends to elevate the potential of the whole system above the earth, and if the neutral is grounded at two or more places, earth currents of triple frequency will result. This phenomenon has been observed and reported, so that the possible effect of grounding the neutral cannot be ignored. Considering electromotive force and current waves of equal amplitude, their effect by induction upon parallel systems will increase with their frequency, so that a triple harmonic may have a considerable effect although its magnitude may be quite small compared with the fundamental wave.

The formulas given by Mr. Taylor for two-wire metallic circuits are, as he says, those commonly given, but do not take into account the presence of the earth. The effect of the earth is given in the following formula,

$$C = \frac{0.07768}{2 \log_{10} \left(\frac{4 h^2 d^2}{m^2 (4 h^2 + d^2)} \right)} \tag{1}$$

where m is the conductor radius, d the conductor separation, and h the altitude above the earth. This formula is deduced from the theory of images. It may be put in the form

$$C = \frac{0.07768}{2 \log_{10} \left[\left(\frac{d^2}{m^2} \right) \left(\frac{\frac{4 h^2}{d^2}}{1 + \frac{4 h^2}{d^2}} \right) \right]} \tag{2}$$

The factor $\left(\frac{\frac{4 h^2}{d^2}}{1 + \frac{4 h^2}{d^2}} \right)$ expresses the effect of the earth, and this is very much less than 0.1 per cent when $\frac{2h}{d}$ has ordinary values in practice. The circuit must approach within a very few feet of the earth before there is any appreciable effect. The same is true of the formula for inductance. It should be stated that these formulas all apply to balanced circuits only, or the condition that at any instant the algebraic sum of the wire potentials is zero and the algebraic sum of the currents is zero. The theory underlying the deduction of all these formulas has been given by Maxwell and Heaviside. The latter has deduced many of the formulas and discussed them in his "*Electrical Papers*."

The theory of images presumes that the earth is a perfectly conducting body of infinite extent, but it is of course well known that this assumption is not borne out. In fact, the vagaries of earth conductivity have long been troublesome and perplexing. This does not of itself destroy the value of the method of images, but it requires a very careful consideration of the effect of the earth's resistivity upon the distribution of earth-return currents. Instead of a true image we find a distorted image, with its centre far below the centre of the true image. The consequent effect is an increase of the inductive phenomena. Much of the experimental work that has been carried on in the field, in connection with the New Haven electrification, must throw a good deal of light on the real character of the image, and it is to be hoped that we may have the benefit of those researches.

Mr. Taylor contends that an ideal metallic circuit is operative, in theory, in a foreign field of any strength. It is true that such a circuit may, by great care and labor, be perfectly insulated and balanced in a strong foreign field, so that it may operate. But under such conditions it possesses a serious defect; it is like a mass in unstable equilibrium. The slightest leak or unbalance throws it out of service, and moreover it cannot be connected or switched to another circuit whose insulation or balance is not high. Besides this, there is the possibility that the circuit as a whole may be elevated in potential, above the earth, to a dangerous degree; if its potential above earth is sufficient, the arresters will discharge continuously. For instance, an exposure, at 30 ft. distance, 20 ft. above the earth, to single-phase trolley conductors carrying 1000 amperes at 25 cycles, for a linear exposure of 30 miles, would keep the ordinary telephone protector in continuous arc until the fuses act. The arresters in these protectors are commonly set for about 350 volts. This potential between line and earth would give painful shocks to persons using the line, should they accidentally place themselves in its path; and it would be certain to shock linemen, and other employes. It seems to the writer, therefore, that Mr. Taylor's contention in this matter is not well founded.

J. B. Taylor: Mr. Scott referred to the fact that the tests on the New Haven road showed no disturbance due to electrostatic induction, and he attributed it to the number of telegraph circuits on the pole line. With this conclusion I agree. Another case where the trolley voltage was the same and the separation of circuits similar, electrostatic induction was felt; but in that case the line instead of carrying twenty or thirty wires, carried only three or four. In other words, the combined capacity of the twenty wires takes up the charging current with a small portion of it on each wire.

Mr. Scott has characterized some of the diagrams as theoretical rather than practical. With that I agree, too. However, one that he picked out (the return conductor with current transformers to prevent return of current by rails and earth) is actually installed in England to meet Board of Trade limitations on difference of potential between points on the rails.

Mr. Copley's tests on allowable induced voltage on telegraph circuits, including simplex, duplex, and quadruplex, are valuable, and their publication, as well as publication of values from tests showing division of current between rail and earth, should be appreciated by all who may be asked to forecast or solve similar problems.

The discussion of relative importance of railways, telegraph and telephone systems, by Mr. Murray, with comparison of electric locomotive records and steam locomotive records and the doctrine of "the survival of the fittest", opens up interesting questions many of which are outside of the scope of my paper under discussion.

Mr. Murray has taken exception to one or two statements in my summary, to which I will reply as follows:

A circuit so installed that it can be touched by one standing on the ground could hardly be classed as "ideal." However, it may be well that he has called attention again to the fact that a quiet telephone circuit may possess a disagreeable or dangerous potential to earth. Regarding his question if the compensating transformer does not provide complete compensation for voltage in the telegraph wire. I must say that the compensation is not *complete* on account of disturbing factors such as earth currents, resistance losses, differences of wave-shape, phase, etc. The compensation may be effecive for certain line and instrument conditions, but not sufficiently complete to be effective for more sensitive systems. With the compensating transformer as with the general problem, it is all a question of relation between final resulting disturbance and sensibility of apparatus.

J. B. Taylor (by letter): I shall have to agree with Mr. Scott's statement that the self-induction of a circuit of two wires separated by 2 ft. is nearly the same as that of a circuit consisting of one 4/0 wire 20 ft. from the earth, if in the calculation the earth is regarded as being a conductor say 400 ft. in diameter with its center 220 ft. from the 4/0 wire. Hence, Mr. Scott seems to be justified in his objection to my general statement applying to diagram *B* of Fig. 20, that a boosted return circuit "will have small self-induction as compared with the usual single-phase circuit with overhead conductor and earth return."

Mr. Copley's later contribution to the discussion gives observed values on inductance of trolley wire with earth return, which are in agreement with the above. More properly I might say that the observed values of self- and mutual-induction give us the knowledge of current distribution in the earth justifying the assumption of such a figure as 400 ft. an equivalent diameter of the (earth) return conductor.

Mr. Copley I think has misunderstood my discussion of the effective position of return current with a single-phase railway. I did not state that " part of the return current would be found in the rails and a part at the image of the trolley wire " but that " the image assumption may also lead to too small inductive values on account of the imperfect conductivity of the earth. " I believe that a smaller value than 200 ft. below the surface of the earth, (that is, ten times the depth of the image) will be found as effective position of return current on single-phase roads of less length than the New Haven, or on roads where the trolley voltage is less and sub-stations at fairly short intervals are necessary.

Dr. Steinmetz objects to my statement that the grounded neutral on a three-phase system is not a likely source of trouble to telephone or telegraph systems, and a contribution from Mr. Fowle also takes up this point. At present I know of one system where slight 75-cycle disturbance is felt on telegraph lines as result of exposure to a 25-cycle, three-phase system with neutral grounded at both generating and receiving points. Some of the transformer magnetizing current at triple frequency returns by earth and is responsible for this slight disturbance. I still feel that with generators of average wave shape and transformers worked at not too high density, the troubles from grounded neutral are small as compared with other possible sources of disturbance.

Mr. Nicholson's contribution gives interesting experience on a long line transmitting large amounts of power. The unusual form of transposition which he describes as having come about through successive changes brings out the fact that the mutual induction between circuits, the planes of whose wires are at right angles, may be zero for certain relative locations.

Mr. Cook discusses the relative advantages from the standpoint of safety of telephone lines grounded at the center point of reactive coils versus the use of the insulating transformers. The telephone line with neutral grounded, is, as Mr. Cook claims, more comfortable to handle, but from the standpoint of safety I believe that too much reliance should not be placed on such a system. The telephone line may be broken or open between the grounded points and the person handling same, so that it seems wise in either case to ground a telephone circuit which is likely to be dangerously charged whenever it is necessary to handle same. The practice in this respect should be similar to the best practice on high-tension lines themselves. The risk from handling such a telephone line is reduced as the number of grounded coils is increased, but this involves increased difficulty in maintaining the line quiet; and I have found many telephone lines which were not sufficiently well balanced to be quiet after such grounded coils were installed, no matter how carefully the coils themselves might be balanced. Grounding the telephone line at more than one point also gives opportunity for earth currents and induced currents of large magnitude to pass over the line, and resistance at joints or unequal resistance of the two sides of the line makes the line noisy with the comparatively large currents flowing.

Regarding Mr. Fowle's suggestion that transformers causing return current to flow in a supplementary conductor should have a ratio other than 1:1, the following considerations seem to apply.

The impedance of the return circuit determines the voltage at which the boosting transformer operates, and with a 1:1 transformer practically the same voltage will be found at the primary terminals as at the secondary terminals. If the ratio is other than 1:1, primary and secondary voltages will stand in the ratio of the numbers of turns and the currents in the two windings will be in an inverse ratio. Since the transformer must be magnetized sufficiently to produce the required voltage there will be some magnetizing current in the primary circuit not found in the secondary. This magnetizing current in a properly designed transformer is a small percentage of the total current, but since this magnetizing current is found in one winding and not in the other it must be returned by way of the earth. In other words, such transformers operate, not as the common transformer at constant voltage and magnetic density, but as series transformers at variable voltage and variable density, depending on the amount of load and impedance of the secondary circuit.

I agree with Mr. Fowle that it would be extremely hazardous to attempt telephone service over a typical 30-mile line at 30 ft. distance from a wire carrying 1000 amperes, 25 cycles, with earth return. I have made no contention that operation in such an extreme case is practicable or even possible with present apparatus and general methods of construction. However, I see no reason to modify my statement that *theoretically* a metallic circuit is operative in fields of any strength and practically can be operated in fields too strong to permit usual telegraphic operation with ground return.

DISCUSSION ON "TELEGRAPH AND TELEPHONE SYSTEMS AS AFFECTED BY ALTERNATING-CURRENT LINES." BOSTON SECTION, OCTOBER 20, 1909

A. S. Richey: My experience in this connection has been almost entirely with the private or operating telephone lines of electric railways. In such cases the telephone lines have been strung on the same poles that support the trolley wire, direct-current feeders, or alternating-current transmission lines. In most instances all four classes of wires were carried on the same pole line. In my first telephone experience in connection with three-phase transmission lines the alternating voltage was 16,000, and our telephone construction (perhaps blindly) followed the old practice where the only interference was from 600-volt, direct-current trolley and feeder. The two telephone circuits, extending about 100 miles, were alternately transposed every half-mile, and the jack-boxes, located at about quarter-mile intervals, were simply wooden boxes with the bottom and lower front entirely open to the weather. The operating contacts were brass posts mounted right on the wood, and consequently formed a pretty good ground on the telephone circuit every quarter-mile. Due to the fact, however, that the ground was the same on each side, the telephone circuit remained in balance, and we got very good results. Our aim in the maintenance of good telephone service was, as Mr. Taylor recommends, "to keep the line in first class condition." Our greatest trouble in so doing was in equalizing the resistance and insulation of both sides of the circuit. Poor electrical connections at joints in the wire affected the first, while tree-grounds, principally, affected the second condition.

Later on, in building another 125 miles of transmission line, the voltage in this case being 30,000, the telephone transpositions were made on a single insulator without cutting the line wires. This greatly reduced the number of joints, and not nearly so much trouble was experienced from loose connections. I have attributed our good service on these telephone circuits: first, to good construction and careful maintenance; secondly, to the fact that the partial ground on both sides of the circuit at every jack-box brought the line, electrically, very near the ground; thirdly, to the probable shielding effect of the 600-volt, direct-current feeder which was carried on the same cross-arm as the telephone circuits.

In most of my experience "the disturbers and those disturbed" have been one. In the operation of several hundred miles of interurban railway, where the train despatching and a great part of the company's business communication between stations, offices, power stations, and sub-stations is done over telephone lines which parallel the company's own transmission lines, the telephone is, in a way, as important as the transmission line—at least one can not well be operated without the other. In such a situation the operator is as much interested in the disturbance as in the disturbing influence, and he must solve the problem.

I think that some protective apparatus such as that described in the paper should invariably be used whenever, as is the case with most transmission lines and interurban railways, telephone wires are carried on the same poles with high-voltage transmission lines.

Sewall Cabot (non member): I should like to point out that where telegraph lines are run on a metallic basis it would be necessary to establish repeater stations wherever it is desired to connect the lines with existing lines run on a ground-return basis. In the case of the telegraph systems on a multiple basis shown in Fig. 5, I should like information concerning an actual test of this method of operation, as in practice I think it would considerably slow down the speed of transmission.

I should like information regarding the commercial feasibility of transposing the three-wire trolley system mentioned in the paper, so as to render the telegraph and possibly the telephone lines immune from inductive disturbances.

John B. Taylor (by letter): The form of telephone transposition referred to by Professor Richey, as made on a single insulator, has come into general use because it is superior to the old form involving several joints in the line. In some cases a telephone line on brackets has been transposed without cutting the line or making use of special transposing insulators, by placing the two brackets on opposite sides of the pole at the transposition point and spiralling the line one-half turn.

Mr. Cabot has raised some practical working objections to the metallic-circuit multiple telegraph system, and as far as I am aware such a multiple system has never been given a commercial working trial.

The three-wire trolley system would naturally be undesirable from the railroad man's point of view. The great difference of potential between the two trolley wires (double the normal working voltage from each wire to ground) would make the general insulation question more difficult, and still further objections and difficulties would be introduced at transposition points requiring section insulators. This and other schemes shown in the paper are given merely as indicating lines of action tending to improve matters. The conditions are always so variable as regards both the transmission and signalling systems that what might be considered impracticable in one case might be found feasible in another.

A paper presented at a meeting of the San Francisco Section of the American Institute of Electrical Engineers, San Francisco, Cal., October 29, 1909.

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SOME PHASES OF TRANSFORMER REGULATION

BY W. A. HILLEBRAND AND S. B. CHARTERS, JR.

The following paper is based upon experiments conducted at Stanford University during the past two years upon the regulation of transformers under varying conditions. The first test was made upon a single phase, 200-watt, 11,000/110-volt meter-transformer. Owing to the importance of voltage and phase regulation in such a transformer, particularly when applied to the measurement of a large amount of power, a knowledge of its behavior in this regard is extremely desirable.

The remaining tests were made upon power transformers variously connected to polyphase networks, for the purpose of determining the cause and probable extent of the unbalancing in polyphase connections that occurs under certain conditions.

The connections investigated were:

Three-wire, two-phase system of distribution.

Open delta.

Scott two-phase to three-phase transformation.

Inasmuch as any transformer in a group feeding into a polyphase network behaves precisely as it would when operated from a single-phase circuit under similar conditions of load and power-factor, the performance of the group of transformers is to be explained on the basis of the performance of its individual units as single-phase apparatus.

In Fig. 1 are shown regulation curves for a 4-kw. single-phase transformer operating at unity power-factor, and at 70 per cent power-factor leading and lagging.

Fig. 2 shows the relation between primary and secondary electromotive forces in the single-phase transformer with a 1:1 ratio, considered as a simple impedance connected across the circuit. The fact we wish principally to emphasize by means of this diagram is that the impedance of the transformer causes not only a variation in the amount of secondary voltages but also a displacement in phase.

With leading current the secondary electromotive force is displaced more than if the power-factor were unity, and still more than if the current were lagging. This general relation is shown in Fig. 3.

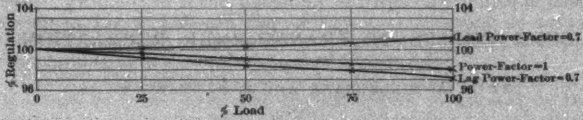


FIG. 1

Meter-transformer. Since in most installations special transformers are inserted between the power mains and the instruments, the accuracy with which the power is measured depends not only upon the inherent accuracy of the instruments but also upon the regulation, both voltage and phase, of the transformers. Thus, if the secondary pressure of the meter-transformer is lower than it should be, due to loading, the power recorded will be less than the real value. Also, if the phase-angle between the currents in the pressure and field coils of the meter differs from that between line pressure and current, a second error is introduced.

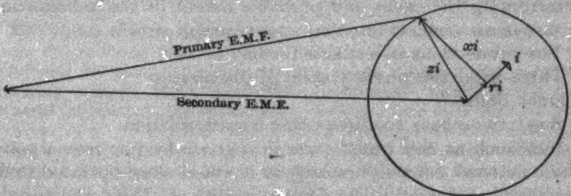


FIG. 2

It is well known that meter pressure transformers are provided by the manufacturer with additional secondary turns to compensate for the drop due to loading, so that when used at their specified load they give their rated voltage ratio; and to give this ratio the load should be as nearly as possible that for which the transformer is compensated. It is comparatively easy in this way to compensate for voltage-drop at any given power-factor, but this will not compensate fully for the drop at a different phase relation between current and electromotive force.

Theoretically it should be possible, by making the resistance very large in proportion to the reactance, to design a transformer of perhaps poor voltage regulation at unity power-factor but one which would give nearly the same drop over a range of power-factors much less than unity.

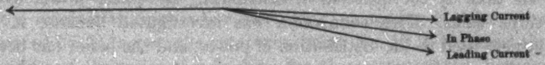


FIG. 3

An effort to accomplish this end might have been made in the transformer tested, in which the dimensions are as follows:

Ratio of turns—100; 1 approximately.
Primary resistance = 5900 ohms.
Primary resistance in secondary terms = 0.59 ohms.
Secondary resistance 0.306 "
Equivalent resistance = 0.896 "
Impedance, in primary terms 9824.0 "
Impedance, in secondary terms 0.9824 "
Equivalent reactance = 0.406 "

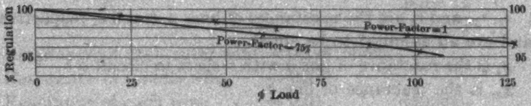


FIG. 4

Voltages—11,000 to 110.
Capacity—200 watts.
Full-load secondary current = 1.82 amperes.

This shows an equivalent resistance of somewhat over twice the equivalent reactance, proportions entirely different from those in the ordinary power transformer, but in spite of this fact the voltage-drop varies widely with the power-factor, as shown by the curves in Fig. 4.

For full-load current between unity and 75 per cent power-factor there is a difference of 1.6 per cent in the voltage-drop, the total drop being for the first case 2.7 per cent and for the second 4.3 per cent; quantities so large where the measurement of any considerable amount of power is concerned as to necessitate, for accurate results, that the transformer be compensated at the factory not only for its specified load but also at the power-factor at which that load operates. Otherwise the meters should be calibrated with the transformers to which they are connected.

Three-wire, two-phase connections. Turning now from the meter-transformer to the subject of polyphase connections, we will take up the question of distributing two-phase power over three wires. This connection was investigated because it is largely used in the distribution of power, and the belief has been expressed that the throwing of quarter-phased currents together into a common conductor will cause voltage unbalancing and phase distortion. This opinion is expressed in a recent and popular laboratory text book, in which a diagram is given to show that such effects are produced. Like so many diagrams of this nature, however, in order to show anything at all the proportions are so greatly distorted that the figure fails to represent practical conditions.

In Fig. 5*a* is given a diagram, the proportions of which are likewise distorted, which, it is believed, takes account of all of the factors in the three distributing wires that affect the voltage as delivered to the receiver.

T_1 and T_2 are the quadrature source electromotive forces.

Φ_1 and Φ_2 are the receiver electromotive forces.

r_1, r_s, and r_2 are the resistances of lines *a*, *b* and *c*, respectively, and are all assumed to be equal.

x_1 is the reactance of line *a* with respect to circuit *a b*.

x_s, is the reactance of line *b*.

x_2 is the reactance of line *c* with respect to circuit *b c*.

i_1, i_s, and i_2 are the currents in *a*, *b*, and *c* respectively.

There is also a transformer electromotive force in circuit, *a b*, induced by current in line *c*, and a similar electromotive force in circuit *b c*, induced by current in *a*, but it is doubtful if these are ever of appreciable value, so they have been omitted from an already crowded diagram.

The impedance drop in the middle wire, $i_s z_s$. Fig. 5*a* does not combine symmetrically with T_1 and T_2 in producing the receiver electromotive forces Φ_1 and Φ_2. It is this fact which causes the increase in phase-angle between the receiver pressures and the difference in their values.

In drawing conclusions from this diagram it must be borne in mind: first, that the resistance and reactance of the individual leads are magnified out of all proportion; secondly, that the currents are assumed to remain equal and in quadrature. In an actual case, particularly if the load consist of induction motors, the last condition will not hold true, because as soon as any unbalancing of voltage or phase occurs, unequal currents with different power-factors are drawn, which check to a large extent the tendency to unbalance.

Two 4-kw. 2200/220- or 110-volt transformers were connected to a receiver through a line 95 ft. long, consisting of three wires spaced 6.5 in. apart, the outer wire being No. 12 B. & S. and the middle of the same wire doubled for 41 per cent of the distance to give the same drop as either of the outer wires.

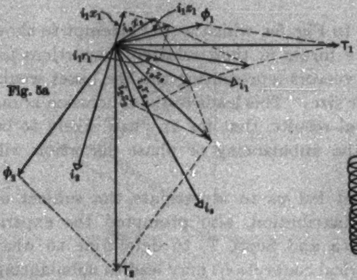


Fig. 5a

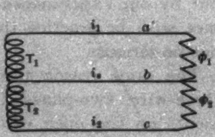


Fig. 5b

Resistance of each outer wire = 0.148 ohms.
Resistance of middle wire = 0.117 "
Reactance of each wire = 0.01 " (about).

The line gave, with full load on the transformers at 110 volts, about 12 per cent drop, and about 6 per cent drop with full load at 220 volts.

The results of a run on non-inductive load are given in Table I.

TABLE I

	Volts		Amperes		Angle phase difference	Per cent unbalance
	Phase A	Phase B	Phase A	Phase B		
No load....	110.4	110.5	0.	0	90° 48′	.09
Load.......	97.4	96.1	34.15	34.05	94° 57′	1.34

These figures, showing an unbalance of 1.25 per cent and phase distortion of 4° 9′, are of interest to the extent that they support the theoretical conclusion that there should be unbalance and phase distortion as a result of this connection.

When furnishing power to an induction motor at 220 volts the figures were, Table II.

TABLE II

	Volts		Amperes		Angle phase difference	Per cent unbalance
	Phase A	Phase B	Phase A	Phase B		
No load....	220.8	220.1			89° 46′	0.3
Load.......	195.2	198.0	18.23	19.8	92° 4′	1.414

Here there was an unbalancing of only 1.11 per cent and a shift in phase of 2° 18′.

In a diagram similar to Fig. 5*a*, which would attempt to show all of the electromotive forces in their relative proportions for our particular line, the vectors representing the line losses would be of almost microscopic size. This leads to the conclusion borne out by our experimental results, that for any case likely to be met with in practice the unbalancing or phase distortion will not be serious.

The same reason that led us to investigate the subject of three-wire, two-phase distribution, also prompted the experiments on the open delta and Scott T, to determine to what extent these unsymmetrical connections may lead to unbalancing or phase distortion.

Open Delta. Fig. 6 shows two transformers connected in V on a three-phase circuit with a three phase, delta connected, non-inductive, load.

The currents in branches *a*′, *b*′, and *c*′ are in phase with the electromotive forces in their respective branches. Current in transformer *c a* is the vector sum of currents in *a*′ and *c*′. Similarly, current in *c b* is the vector sum of currents in *c*′ and *b*′.

In Fig. 7 are shown the vector relations of electromotive forces and currents in the load circuit.

Electromotive forces *a*′ and *b*′ are also the transformer electromotive forces *c a* and *c b*, respectively. See Fig. 6. The sum of currents in *c*′ and *a*′ is *c n* and the sum of currents in *c*′ and *b*′ is *c m*.

An inspection of this Fig. shows that in transformer *c b* the current is lagging by 30° and in transformer *c a* it is leading by the same amount. That is, each transformer, on non-inductive load, operates at 86.6 per cent power-factor. The result of this can be readily seen by referring back to Figs. 1 and 3. The effect of leading current in transformer *c a* is to hold up the secondary voltage and shift it in phase behind its phase position on no load. In transformer *c b* the lagging current causes a greater drop in voltage, but shifts the phase less than in the other.

In Fig. 8 the triangle *c a b* represents the balanced electromotive forces of Fig. 6. Triangle *c a′ b′* shows the electromotive forces on non-inductive load.

The effect of drawing load has been to destroy the equality of voltages and to change the angle between the two transformer electromotive forces.

It should be borne in mind that the angle between the transformer pressures *a c*, *b c* and *a′ c*, *b′ c*, Fig. 8, is actually the exterior angle *c*, or 180 degrees minus the angle here given. Thus, the actual effect of the delta connection is slightly to increase the angle between the two electromotive forces. For convenience in graphical representation the supplementary angle has here been treated.

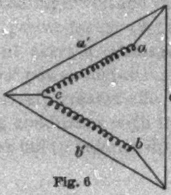


Fig. 6

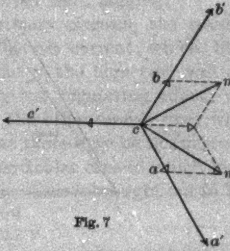


Fig. 7

In table III are shown the results of loading two 10-kw. transformers in this manner.

TABLE III

	Electromotive force			Per cent unbalance	Angle ' C ' Fig. 8
	Phase 1	Phase 2	Phase 3		
No load................	254.4	253.2	253.4	0.47½	59° 58′
Load..................	246.6	240.3	236.6	4.05	58° 13′

Balanced non-inductive load, 50 amperes per phase. Phase 3 is the open phase.

With these particular transformers carrying approximately full-load current, there was an unbalancing of 3.58 per cent and a change of 1° 45′ in the phase-angle between their pressures. A convincing demonstration of the fact that the current in one transformer is leading was obtained by inserting a choke-coil in series, which caused an immediate increase in wattmeter reading, the current and voltage remaining practically the same.

The regulation on non-inductive load is chiefly of theoretical interest. The induction motor when operated from such a system exerts its customary regulating effect so that unbalancing and phase distortion are by no means so pronounced. Unfortunately, we had but one three-phase motor, which could load the transformers to only about half of their capacity so that regulating effects were not very marked. In Table IV are presented, however, comparative readings on non-inductive and induction motor loads of approximately equal value, which show relatively a greatly improved performance on inductive load over that on non-inductive load, although the unbalancing in either case was slight.

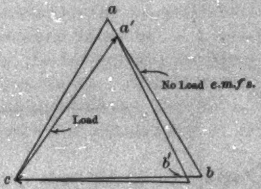


FIG. 8

TABLE IV

	Electromotive force			Per cent un-balanced	Angle	
	Phase 1	Phase 2	Phase 3			
Non-inductive Load	232.1	230.3	231.7	0.776	60° 12′	no load
	229.2	224.4	223.9	2.31	59° 11′	load
Inductive load	233.6	230.2	232.1	1.45	60° 3′	no load
	226.0	224.3	222.5	1.55	59° 21′	load

Phase 3 is the open phase. The currents were 27.9 and 27.2 amperes per phase for the non-inductive and the inductive loads respectively.

For the non-inductive load the unbalance and phase distortion were 1.53 per cent and 1° 0′. For inductive load they were 0.1 per cent and 0° 42′ respectively.

The above results are of value only as a check upon the theory that explains the regulation of V-connected transformers. In the most unfavorable case, when full-load current was drawn by a non-inductive receiving circuit, the unbalance was between three and four per cent. On inductive load the unbalancing would doubtless be considerably less, so that, judging from the performance of these two 10-kw. transformers, which are representative of modern apparatus, the unbalancing resulting from the V-connection or open delta is not likely to be serious, a conclusion doubtless in accord with practical experience.

When supplying induction motors with power-factors of from 85 per cent to 90 per cent, one transformer operates at about unity power-factor and the other operates at a power-factor of from 50 per cent to 55 per cent, lagging.

With initially unbalanced primary circuits, the transformer with the high voltage draws a heavier current, which, however, if the power-factor of that circuit is the high one, will on that account exert a correspondingly less regulating effect; whereas the low power-factor current in the other transformer will exert a relatively greater effect, so that there may be no improvement in line conditions with load, a particular case in which induction motors fail to balance up the line. This is brought out in Table V.

TABLE V

	Electromotive forces			Currents			Per cent un-balance
	Phase 1	Phase 2	Phase 3	1	2	3	
No load	230.1	216.8	223.8	0	0	0	5.8
Load	225.0	212.2	218.6	24.0	19.4	26.15	5.7

Referring to Fig. 6, phase 3 is the open phase *a-b*. Currents 1 and 2 are currents in transformers *a-c* and *b-c* respectively. Current 3 is the current in the lead wire from the junction point *C*.

Theoretically, then, the V-connection of transformers will cause unbalancing, due to the different power-factors at which the two operate; but with well designed apparatus supplying induction motors, this unbalancing should be small. With initially unbalanced circuits conditions may be such that the induction motors fail to exert any regulating effect.

These conclusions are based upon experiments in which the electromotive force was nearly sine wave in form. Where a pronounced third harmonic is present the pressure across the open side is much distorted, which might cause trouble aside from any phase distortion or unbalancing of the fundamental.

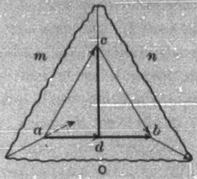


FIG. 9

Scott T-connection. Fig. 9 gives the phase relation of current and electromotive forces in a system of two transformers T-connected, supplying power to a balanced, non-inductive load. *a b* represents one transformer and *c d* the other.

From this diagram it will be seen that currents of different phase relation flow in the two halves of the transformer which constitutes the top of the T. In one half, *a d*, the current is leading by 30 degrees and in the other half lagging by the same amount. This means, according to the curves in Fig. 1, that the regulation in the two halves will be different. Side *a c* of the delta electromotive forces will tend to hold up its voltage and side *b c* to drop off.

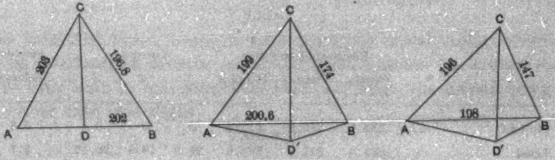


FIG. 10

This is shown in Fig. 10, which represents to scale, no-load, half-load, and full-load voltage readings taken with the two 10-kw. transformers used in the tests on the open delta. The lines *a d′* and *d′ b* show that the arithmetical sum of the voltages in the two halves of the transformer *a b* is no longer equal to the electromotive force between its terminals. The unbalance from no load to full load was 22.7 per cent.

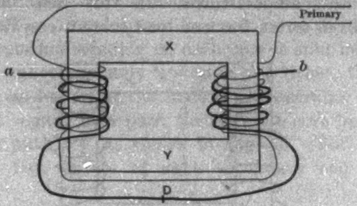


FIG. 11

These transformers are of the core type, with a primary and a secondary coil on each leg, wound for 2200 or 1100 to 220 or 110 volts.

In the run represented in Fig. 10 both primary and secondary coils were connected in series. That is, one-half of the secondary,

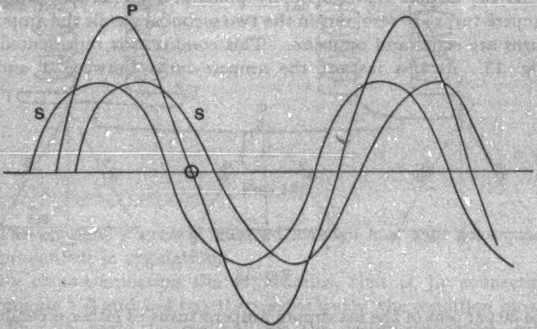


FIG. 12

represented by vector *a d* Fig. 9, occupied one leg, and the second half *d b* occupied the other leg. This is shown in Fig. 11.

The significance of this fact is as follows: in ordinary single-phase operation the ampere-turns between points *x* and *y* on the core are zero. That is, there is no magnetomotive force tending to establish leakage flux via the route *x y*. When, however, leading current flows in leg *a d* and lagging current in leg *b d* this is no longer true

In single-phase operation the draught of load-current draws current from the primary whose ampere-turns neutralize the secondary load ampere-turns. In this case, however, with primary coils in series, but one load-current can flow, which can only neutralize the vector sum of the two secondary currents. This relation is shown in Fig. 12, which represents the primary and secondary currents reduced to a 1:1 ratio.

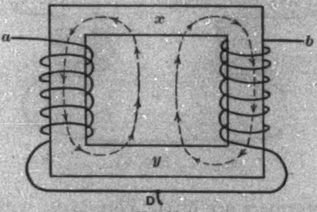


Fig. 13

At the instant represented by point *o*, Fig. 12, the primary ampere-turns are zero, but in the two secondary coils the ampere-turns are equal and opposite. This condition is represented in Fig. 13. At this instant the ampere-turns between *x* and *y* are 50 per cent of the maximum ampere-turns of either secondary coil. The result is an enormous leakage flux with consequent atrocious regulation. So great was the leakage flux with our particular transformer that the case became hot, due to eddy-currents set up by the stray field.

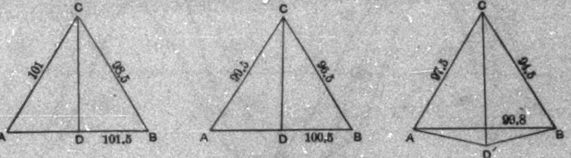


Fig. 14

With primaries in series as before, but secondaries in parallel, furnishing 110 volts, instead of 220, the regulation is greatly improved, as shown in Fig. 14, which represents no-load, half-load, and full-load voltage readings with the secondaries of both transformers in multiple.

The unbalancing from no load to full load is 2.3 per cent as against 22.7 per cent for the series connection.

When secondaries are connected in parallel the condition represented in Fig. 12 holds true for each leg of the transformer; but as the secondary winding on each core is split into two concentric coils, one completely covering the other, the ampere-turns of the two halves at the instant *o* neutralize each other, not only with regard to a path through the core but also with regard to the path *x y*, as shown in Fig. 15. For the sake of clearness the two halves of each secondary coil are shown separately.

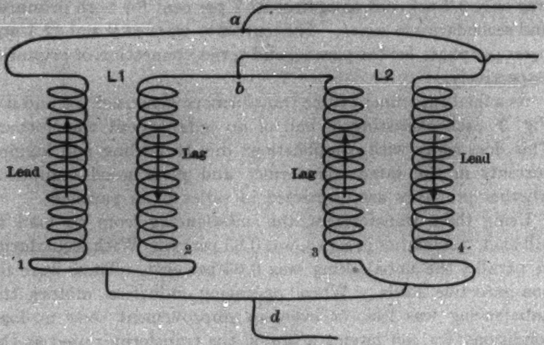


Fig. 15

The result is a greatly reduced leakage flux with consequent improvement in regulation.

By cross-connecting the secondaries, that is, by connecting terminals 1–3 and 2–4 together respectively, the condition shown in Fig. 15 could be realized for the series connection, with secondary voltage of 220, and good regulation would result, but the regulation with secondaries in parallel would then be poor.

As a further experiment, the two halves of the primary winding of transformer *a b*, Fig. 9, were each excited by means of separate transformers at 1100 volts, equivalent to placing the two primary coils in parallel across an 1100-volt circuit. With secondaries connected in series, the secondary current in one leg is leading and in the other lagging, but with each primary coil supplied independently of the other, it could draw a load current whose ampere-turns would at all times equal those of its corresponding secondary, as in the single-phase transformer. The result was small leakage flux and good regulation.

TABLE VI

	Electromotive forces			Per cent unbalance	Average amperes per phase
	Phase 1	Phase 2	Phase 3		
No load........	221.8	220	220	0.82	
Load...........	200	194.6	192.0	4.0	41.9

With this connection the unbalance from no load to full load was only 3.2 per cent as against 22.7 per cent for both primaries and secondaries in series. The currents were 41.9 and 47.1 amperes per phase for the parallel and series connection of primaries respectively.

As a final experiment three transformers were used, *a b* and *d b*, Fig. 9, each consisting of half of an independent transformer. This does away with complications due to leading and lagging currents in the same transformer and gives good regulation whether primaries are connected in series or in parallel.

Using three transformers, the unbalancing from no load to full load, secondaries in series, was 0.85 per cent. With secondaries in parallel the unbalancing was 0.63 per cent. These were for non-inductive loads. When operating induction motors the unbalancing was less, or even an improvement over no-load conditions; for, not having a tap on the transformer used as the stem of the T that was approximately 86.6 per cent of the base, the secondary voltages were initially unbalanced between one and two per cent.

Our tests were all based on transformation from two to three phases. When transforming from three to two phase, it is the primary of one transformer that carries different power-factor currents in its two coils, but the effect would be the same as with similar currents of equal ampere-turns in the secondary coils, so that any conclusions drawn from these experiments should apply equally well to both cases.

Wherever serious unbalancing is caused by T-connected transformers transforming from two to three phase, or the reverse, it is probably due to excessive leakage flux caused by different power-factor currents that circulate in the two halves of the transformer comprising the top of the T. This leakage flux may be greatly reduced and regulation correspondingly improved:

1. By proper interlacing of the transformer windings; secondaries if transformation is from two to three-phase; primaries if the reverse.

2. By joining in multiple the two halves of the transformer used as the top of the T, on the side that connects to one of the two-phase circuits.

3. By using three transformers, where available.

In conclusion, we wish to acknowledge our obligation to Professor Harris J. Ryan for the assistance which we received from him on numerous occasions during the conduct of these experiments.

DISCUSSION ON "SOME PHASES OF TRANSFORMER REGULATION." SAN FRANCISCO, OCTOBER 29, 1909

F. E. Geibel: The paper tonight has been very interesting, more so because we have had actual tests from which the conclusions have been drawn. As explained, the action of transformers in groups, or in banks, depends on the action of the single-phase transformer, and the authors have touched briefly on the single-phase transformer and meter potential transformer before going to the banks.

Unbalancing on the banks of transformers, as we have seen, is largely taken care of by the induction motor and synchronous apparatus. Again, in the case of power transformers, or transformers for delivering power, we are not so much concerned in the phase angle difference; what we want on the other side is voltage, and with as little drop as possible. As the regulation is affected at high power factors mostly by the resistance, and at low power factors mostly by the reactance, in a well designed transformer, both are kept as low as possible. In the case of the meter transformer, however, the phase angle difference between the secondary and primary e.m.f's. plays a more important part and affects considerably the wattmeter readings.

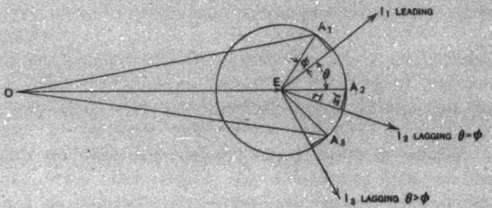


FIG. 1

The authors have found that, in the meter transformer under test, the equivalent resistance is about twice that of the equivalent reactance. Since the power factor of an alternating current circuit is the cosine of the angle whose tangent is x/r, we have for the power factor of this transformer, 0.91 approximately.

In the accompanying diagram OE represents the secondary e.m.f., EI_1, EI_2 and EI_3, the secondary current at different power factors, and A_1O, A_2O and A_3O the corresponding primary e.m.f's. From the figure it is seen that on passing from leading current to lagging current, the angle of lag exceeding the angle of lag of the transformer, we pass from a condition of lagging to a condition of leading phase angle difference between primary and secondary e.m.f's., the two e.m.f's., being exactly

180 degrees apart when the power factor of the load is made the same as the power factor of the transformer.

The power factor of a meter load is approximately 0.75 to 0.8 and on the meter transformer under discussion, a load of this character would give a condition of leading phase angle difference. Thus, while the poor regulation of the transformer would cause a wattmeter to indicate low, the leading phase angle difference decreases the angle between current and potential and causes the meter to indicate high—the two effects to a large extent neutralizing.

The meter transformer, although not showing up so well when regulation alone is considered, has been found to be very accurate, especially when used on loads for which they have been designed.

In the July number of the PROCEEDINGS Mr. Robinson has gone into this matter very thoroughly and has also taken into account the phase angle difference of the meter itself.

W. F. Lamme: The problem of transformer regulation is usually a very important one. As noted in tonight's paper, there are three elements to be considered:

First—The ohmic resistance.

Second—The inductance.

Third—The leakage flux.

In the paper is given a case in which large flux leakage takes place, with certain connections. But in every transformer there is a slight leakage between the primary and secondary coils, and this leakage is different in different transformers, and even in different arrangements of coils in the same transformers. The more closely interlaced the primary and the secondary coils are, the better is the regulation, and vice versa. In other words the more perfectly the magnetic flux set up by the primary coils is forced through the secondary coils, the better the regulation. This is, or should be, a question of considerable interest to all engineers. But, I believe, definite information upon the subject is largely confined to factory circles.

It is interesting to study the regulation of transformers with non-inductive and with inductive load. With a non-inductive load the regulation of a transformer is, of course, nearly equal to the ohmic drop, and the inductance has little effect. With an inductive load the inductance of the transformer comes into effect, and the effect of the resistance is lessened, depending upon the power factor of the load. From the above it may be inferred that the regulation of two transformers may be different with non-inductive load, and nearly the same with inductive load.

In recent years more care has been given to this question of regulation for lower power factor. The point just mentioned is best illustrated by two sets of curves. One showing the regulation of a series of transformers from one to fifty kilowatts operating with non-inductive load. The second curve showing the same transformers operating with an 80 per cent power factor load. In these sets of curves are three types of transformers. A core type, a shell type, and one of the newer types of transformers. At 100 per cent power factor you will note all of the types agree very closely in regulation, taking them size for size. But the regulation is poorer the smaller the size of the transformer. All this is natural, and to be expected, for economical design limits us to this condition. But at 80 per cent power factor the regulation of the same sizes are wide apart. And the regulation of the older type is quite erratic, whereas the regulation of the two newer types are not so erratic. Also note that the newer types have nearly the same regulation from the smaller to the larger sizes.

As to transformers for operating meters, we note from the paper that these transformers are compensated for the conditions under which they are supposed to operate. This is important. If the transformer is compensated to operate say, one wattmeter, correctly, the same transformer will not operate two wattmeters correctly. And in the second case there may be an error of several per cent. Therefore, in the purchase of such transformers, it should be the practice of the party purchasing the same to name the conditions of operation.

Combinations of transformers to change from three-phase to two-phase, or from two-phase to three-phase, are made at the expense of regulation, as well as at a loss in efficiency. By the example in the paper, you see that it is important to know how to make some of these combinations properly. Otherwise the regulation and losses will become excessively bad. And, as a result, there may be a burnout of one of the transformers.

Mention was made in the paper of unbalanced primary voltages and their effect on the secondaries. This is a very important matter, especially in power transmission work. In such work we rarely see balanced conditions on the delivery line. Sometimes the unbalancing is very bad. I have in mind one case of a 30-h.p. three-phase induction motor operating from three 10-kw. transformers. One of the three transformers burned out without apparent cause. Our investigation showed the division of load between the three transformers as follows: First, 14 kilovolt-amperes; second, 10 kilovolt-amperes; third, 6 kilovolt-amperes. The 14-kilovolt-ampere transformer burned out, due to unbalanced condition of line. The above transformers were at first connected delta to delta. They were changed to delta primary, star secondary, after which the loads divided much better than they did at first.

B. G. Lamme: The authors of the paper of the evening have called attention to the unbalancing or distortion of voltage and phase which may be obtained with various unsymmetrical combinations of transformers. They have also stated that induction motors tend to reduce such distortions. It may be added that synchronous motors and converters also tend to reduce the distortion. But all such correcting effect is obtained at a certain expense, usually in the capacity of the correcting apparatus.

Distortion of phase, and of voltage, both tend to produce unequal currents in induction and synchronous motors, including converters. If one leg of a supply circuit is of higher voltage than the others, while the motor generates equal counter e.m.f's., current will so flow in the motor that the motor e.m.f's. are distorted in the direction of the line distortion, while the currents tend to correct the line e.m.f. The limit is when the line and motor come to balanced condition with respect to each other.

This unbalancing in the currents affects the capacity of the motors. The total copper loss may not be greatly increased, but the losses in individual coils, or circuits, will be changed. At the limiting capacity of the motor, the heating of individual coils fixes the rating, as a rule, and not the loss as a whole. Any unbalancing in current, therefore, affects the heating of the individual coils, and thus reduces the limiting capacity. This is true for induction and synchronous motors. But for synchronous converters the case may be still worse.

In converters, the armature copper loss is normally much less than with a corresponding direct-current machine, or if the converter was run as a straight direct-current generator. This is due to the fact that the same winding is used for the incoming alternating current and the outgoing direct current. Part of the alternating current input is fed directly in the direct current, while part is transformed to mechanical energy, and back to direct current electrically. In consequence, when transforming three-phase to direct current, the armature copper loss is only 57 per cent of straight direct current operated with same armature while with two-phase (or four-phase in reality), it is 38 per cent, and with six-phase it is 26 per cent. But this 26 per cent loss is not uniformly distributed in the armature. The average loss in the various armature coils depends upon their position with respect to the tap-offs to the collector rings. The highest loss is next to the tap-off, this being about 60 per cent of direct current Therefore, the coil next to the tap-off is liable to be overheated under extreme condition of load.

If the power factor is not 100 per cent, then this loss curve is greatly affected. At about 95 per cent the loss in the tap-off coil goes up about 100 per cent. And at still lower power factor it goes much higher. Therefore, a low power factor greatly reduces the ultimate capacity of a converter, depending upon the size, and general design of the windings, number of phases, etc. Unbalanced voltages or phases, due to unsymmetrical transformer combinations will have a bad effect on the capacity of any converter, and care should be taken, with such machines, to furnish balanced supply conditions.

The fact may be of interest that 60-cycle synchronous converters, as a rule, can be operated at lower power factors than 25-cycle converters as normally constructed. This is not due to any peculiar merit of 60 cycles, but is due to the fact that 60-cycle converters usually have many more poles than 25-cycle, and if parallel wound, as is usually the case with large sizes, the smallest armature strap conductor which is safe for mechanical reasons, is much larger than necessary for electrical purposes.

It has been found in practice where unsymmetrical transformer combinations have been used for step-up purposes, that a similar arrangement should be used for stepping down. For instance, if the Scott, or T combination is used to step up from two to three-phase, then a T should be arranged for stepping down to motors, with the head of the step-down T across the same wires as the head of the step-up T. The same is true of other unsymmetrical combinations. In this way some of the inequalities cancel instead of accumulate.

In connecting unsymmetrical transformer combinations in parallel, there is usually a possibility of cross currents between them, unless all are arranged across the polyphase lines in a similar manner.

In conclusion it may be said that all unsymmetrical systems should in general, be avoided. Such systems originate, as a rule, in an attempt to save in first cost of a system or installation, but in the end they are generally much more expensive than true balanced systems, when reduced capacity of apparatus, etc., are taken into account.

J. W. White: In regard to the inquiry on the effect of frequency changes upon the accuracy of primary recording wattmeters, and particularly upon a 60-cycle meter operating upon a 25-cycle circuit, I would say that in the first place the potential coil of the meter would probably burn out on account of the excessive current. The potential transformer might do likewise, as the capacity of a 60-cycle transformer operating on a 25-cycle circuit is but 69 per cent of its rating, due to excessive magnetizing current. However, if this did not occur the meter would run fast.

Consider first the potential transformer.

In the ideal potential transformer the phase displacement in the secondary circuit would be offset by a capacity effect, and in Fig. 2, $O\,E$ or $O\,B$ would be the impressed e.m.f. and $O\,a$ would be the effective e.m.f.

If, however, the phase angle of displacement is leading or lagging, a condition will exist similar to $O\,B$ or $O\,BB$. If operating on a lower power factor, $R\,I$ would remain constant with $X\,I$ diminishing in proportion to the frequency. If $O\,E$ and $O\,a$ coincide, a lowering frequency would have no effect inasmuch as the inductive reactance is offset by the capacity effect and thus the effective e.m.f would be higher and the amount of compensating effect in the transformer's secondary winding can be less.

If, however, the reactance effect in the transformer is leading or lagging to produce $a\,BB$ or $a\,B$, then the phase displacement of the transformer is equal to $BB\,O\,E$, or $B\,O\,E$.

If, as in Fig. 2, ($BB'\,a''$) the power factor of the circuit (not the transformer) passes from leading current to lagging current, the angle of lag exceeding the angle of lag of the transformer, the angle of phase distortion with reference to the secondary is further increased, while on the other hand if the power factor of the circuit is leading and the power factor of the transformer lagging the two would tend to compensate and cut down the angle of phase displacement.

The same condition would exist if the opposite were true, *i. e.* if the angle of phase displacement of the transformer were leading and the power factor of the circuit were lagging the two would tend to compensate, while if the power factor of the circuit were leading the resultant phase angle with reference to the secondary of the transformer would be greater.

From the above it is at once evident that in lowering the frequency $X\ I$ would be diminished and whether leading or lagging would cause the angle $B\ a\ E$ to be decreased and thus reduce the angle of phase displacement.

From the above can be deduced that lowering the frequency of a potential transformer will tend to reduce the phase angle of displacement if leading or lagging. (This would, if any thing, cause the meter to run faster.) If the transformer capacity is balanced by the inductance there will be relatively no change.

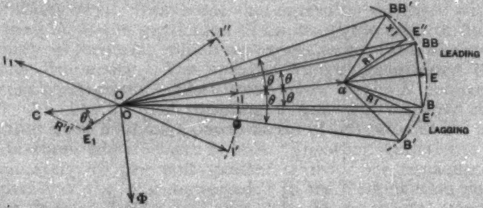


Fig. 2

With regard to the regulation of the transformer and the effect of the resistance of the coils upon regulation, let the line I represent the harmonically varying flux in the core. $O\ a$ represents the useful part of the primary electromotive force and $O\ c$ the total electromotive force induced in the secondary coil. The line $O\ I$, represents the secondary current and the line $O\ I''$ represents the primary current. The total primary electromotive force E' exceeds $O\ a$ by the amount $R\ I$ (parallel to I') and the electromotive force E, at the terminals of the secondary coil falls short of $O\ c$ by the amount $R'\ I'$ parallel (to I_2).

When the angle θ ($a\ O\ I'$) is nearly zero (secondary receiving circuit non-inductive) then $R\ \ I$ and $R'\ I'$ are nearly parallel to Oa and $O\ c$ respectively, so that $O\ a$ is much less than E' in value and E' is much less than $O\ c$ in value. On the other hand, when the angle θ is nearly 90 deg. (secondary receiving circuit containing a large inductance of a condenser) then $R\ I$ and $R'\ I'$ are nearly perpendicular to $O\ a$ and $O\ c$ respectively, so that $O\ a$ is nearly equal to E' in value and E_1 is nearly equal to $O\,c$ in value. Therefore the regulation of a transformer is largely affected b coil resistance when the secondary receiving circuit is non inductive, but scarcely at all affected by the coil resistance when the secondary receiving circuit contains a large inductance or a condenser.

This accounts for the even regulation curve shown by Mr. Lamme illustrating the regulation of the type S transformer operating on low power factor, and this is characteristic of any type of transformer (multiple) operating under the same conditions.

With regard to the operation of the meter on 25-cycles refer to Fig. 3.

Let $O\,E$ = Impressed e.m.f.
$O\,C$ = Current non-inductive.
$O\,C'$ = Current inductive.

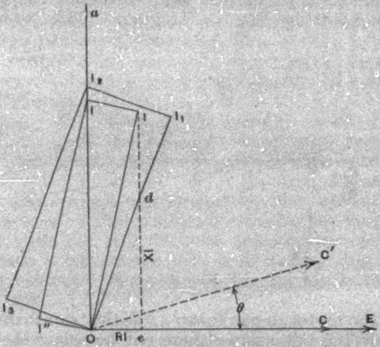


FIG. 3

$O\,I$ = Current in potential circuit.
$O\,I''$ = Current in lagging coil.
$O\,I'$ = Resultant current effect in potential circuit.

From the above it is at once evident that with a lowering frequency the impedance of both the potential and lagging windings will be decreased and the current flow, therefore, increased, thus increasing $O\,I'$, causing the meter to run fast.

In addition to this it is also evident that with the decreased frequency the reactance factor of the potential circuit, *i. e.* $X\,I'$ will be decreased 5/12, *i. e.* 25/60, making $X\,I$ equal to $d\,e$ instead of $I\,E$. This will bring the angle of lag of the potential winding to $O\,I_1$ making it necessary, therefore, to add an increased effect on the lagging coil to bring the resultant effect back to I_2 as the recorded power of the meter is equal to $O\,C \times O\,E \cos O$, and if the meter is not corrected it is therefore evident that with

OI' increased and an error introduced equal to IOI_1, the correction factor would be $\cos IOI_1 + OI_2 - OI'$. In commercial service a pertinent example is noted in meters designed for operation on both 140 and 60 cycle circuits, which are double lagged, one coil being left open circuited on 140 cycles but short circuited through resistance when operating on 60 cycles.

From the above, therefore, three points are evident:

A. A lower frequency will reduce the error of phase displacement in a transformer except wherein a unity power factor condition exists in the transformer winding. In this latter case there will be no change.

B. The regulation of transformers is vitally dependent upon resistance of its windings and its relative regulation is not affected as greatly on low power factor as in comparison with high power factors.

C. Integrating meters operating on lower periodicities than that for which they are designed will run fast and the effect of a lower frequency on the primary transformer for such a meter will be cumulative with that of the meter itself.

S. G. Gassaway: I was somewhat agreeably surprised with the paper tonight as the gentleman did not include a lot of difficult mathematical formulae, which we expect to get from one coming from the University. The speaker tonight mentioned the V and Scott connections. The power factor of the V connections is 86.6, this has another meaning if you will consider it. It means that if the load has a power factor of 100 per cent the power factor in these transformers is 86.6. In other words, you have approximately 15 per cent greater transformer capacity than the capacity of the load connected. In the T connection we have a power factor of 92.8 per cent. In other words, you have something like 8 per cent more kilowatt transformer capacity than you have load connected.

The regulation of a transformer is really a sort of measure of the care with which it is constructed. A more carefully constructed transformer has better regulation. Regulation is important in the transformer that is being used for lighting, because the candle power of the lamps varies with the potential. In converter work, regulation is not so important because it can be taken care of by series reactive coils which allow for line drop, etc. and thus you obtain any regulation desired. Likewise with motor generators the regulation of the transformers is not important.

Regulation depends on a number of factors, one of which is the reactance or impedance of the transformer. If the transformer is not carefully constructed, and there is considerable flux leakage, that means the impedance is higher; in other words, poor regulation.

In the smaller sizes of transformers, we find the transformer is generally of the core type, because it is cheaper to make and it is lighter, but it has not in general as good regulation as a transformer of the shell type. The reason for this is obvious, because in the shell type transformers there is a better opportunity for interlacing the coils thus preventing magnetic leakage. There are other reasons for using the shell type, especially in larger transformers, than that of regulation alone. In the shell type the coils can be arranged more advantageously for cooling and thus prevent hot spots which would be likely to occur were the very large capacity transformers made in the core type. It is possible to brace the coils more securely in the shell type, repairs are more readily made, and there are many other features which make the shell type desirable in large capacities.

Some of the first transformers that were designed had very poor regulation notwithstanding the care taken in designing them, and on investigation the cause was found to lie in the large eddy current loss in the casing due to the case being located too close to the core, thus causing a large flux leakage. On experimenting it was found that there would be little or no loss in the case if it were not located closer than three inches to the core.

The impedance of the transformer varies greatly with the spacing or arrangement of the coils. Some experiments were made on the core type of transformer on varying impedance, and it was found that impedance could be varied from 2.4 per cent to 150 per cent by spacing the coils. We found that when we had all the primary coils on one leg and all the secondary coils on the other leg of the transformer coil, the impedance increased until we reached as high a figure as 150 per cent, depending on the number of coils and how well those coils themselves were placed on the transformer.

The regulation of a transformer has another feature to be considered. We know the load divides itself amongst transformers in bank according to the relative admittance, I believe it is called, which is commonly taken as the kilowatt capacity divided by the impedance volts or the percentage in impedance volts. As I said, the regulation depends on the impedance; theretore, if the impedance is large, the regulation is poor, the relative admittance would be small, and we find that the transformer does not take its proper share of the load if it is connected with transformers that have better regulation.

C. L. Cory: I am very much interested in the paper this evening because it has given us an opportunity to understand the regulation of the transformer in a much broader sense than we do ordinarily. Summing up what has been said by the different speakers this evening it may be said that the regulation of a transformer, except as regards the change of the load, depends upon the resistance and reactance, and, by the way, reactance does not always mean inductive reactance, but it may mean condenser reactance as well. The regulation of a transformer, again depends upon leakage. An ideal transformer would be one in which the primary turn and each secondary turn occupy exactly the same physical space.

The paper this evening has interested all of us because it takes up the transformer from two different points; one, the transformer which is used for meter purposes, that is the potential transformer, and the other, the practical transformer, which Mr. Lamme has chosen to call, the unsymmetrical transformer.

A number of people in this room probably remember the series of tests made about two years ago where it was decidedly important to determine the accuracy of meters working not on 60 cycles, but on 50 cycles; where the current was to be 10,000 measured volts; where the power factor would vary between 100 per cent and 80 per cent and where the magnitude of energy was to be about 5,000 kilowatts.

The checking of meters was a simple matter, but the checking of potential transformers and series transformers was an entirely different matter, and inasmuch as in this particular case an error of about one-half or one per cent represented a loss or gain to the company of about $5,000, accuracy was of some consequence.

To get at the method of determining this phase relation of primary and secondary between transformers of one manufacture and one of different manufacture, they were sent to the bureau of standards, and these transformers were operated not exactly at 60 cycles, but at 50 cycles, 48 and 52 cycles, and were connected as per instructions at the bureau of standards with reference to a standard 150-volt 200-ampere indicating instrument, and also each transformer of its particular type to a 5-ampere wattmeter that was used to measure the power. When these results were turned over to the company having charge of the tests it was found that the capacity of potential transformers had a great deal to do with the regulation; in other words, it determined that while one transformer had a great deal of insulation the other one did not have so much.

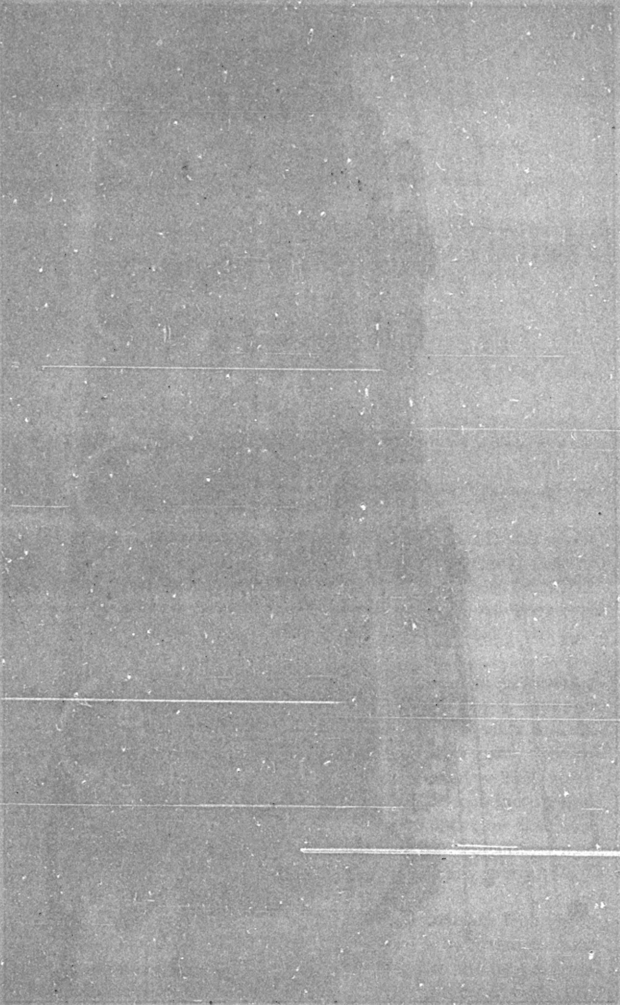
I should say that it was exceedingly dangerous, and subject to a very great error, to use a transformer and meter which were designed for 60 cycles on a 25-cycle circuit. In the first place you are running a very great risk of burning out your potential transformer, but under any circumstances I doubt very much whether, unless you knew definitely the curve showing the relation of the phase angle and the power factor, you could ever tell whether your meter was reading fast or slow. I am not quite sure but that under some conditions the meter would read fast and under others it would read slow.

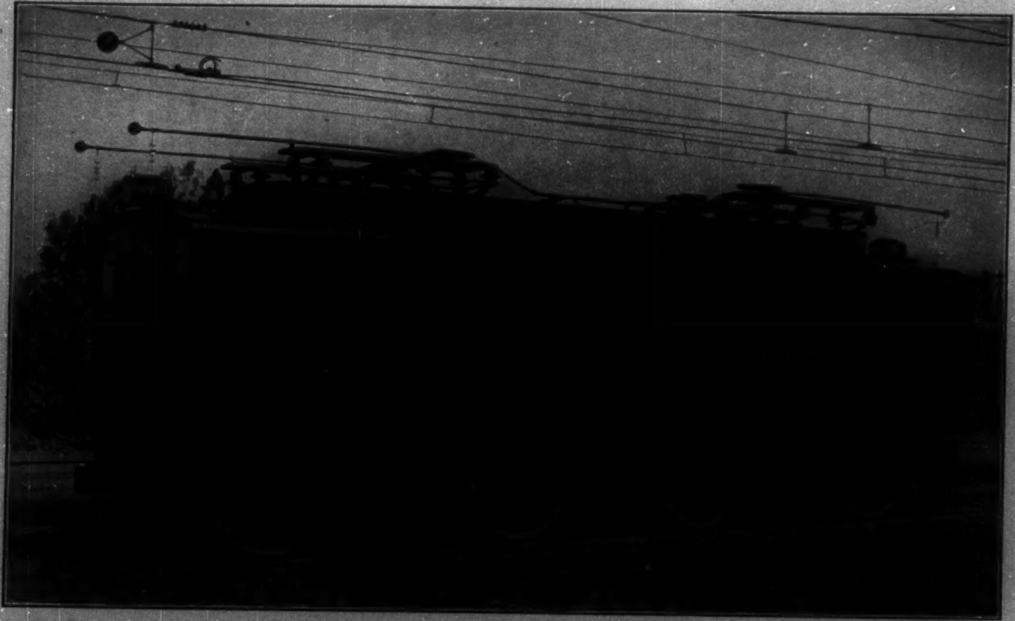
F. V. T. Lee: The trouble particularly in regard to two-phase and three-phase or T connection has been well known in the past, but I think this is probably the first time that a good many of us have had an opportunity of having somebody explain the true inwardness of the trouble. I remember one case that may be of interest where a plant was installed in the northern part of California, and for reasons of economy it was necessary to use three-phase transmission. It was desirable to take two-phase machines and connect them for three-phase with the T connection. For some reason it was necessary to use two-phase motors. Some strange results were obtained, and what really happened was exactly as illustrated by the authors this evening. Unfortunately the winding of the generator did not allow for adjustment and the result was that special generators had to be built, which overcame the trouble, and when received from the factory the generator leads and the motor leads were all carefully tagged as to how they should be connected, so no mistake could be made.

Those days have gone by, but it is necessary to have papers of this character, so that those who have not given it special attention will look out for it, and those who have met the trouble will see the solution. These academic papers really should not be stigmatized as being academic, for the reason that they come from the University where they have the time and opportunity to give these problems theoretical treatment, which those in practice haven't time to do.

G. C. Holberton: Apparently the discussion of the paper has shown us that there are errors of regulation. The author referred to regulation of power transformers, or lighting transformers such as we are using in practice, and that particular regulation is a matter that we can watch and if it is a very serious thing we notice it, but in the matter of transformers used for meters we cannot. I think for that reason we should go into it even further than has been gone into tonight. In the discussion tonight, as I take it, it has been brought out that there are errors, all of which are over one per cent. If these errors are cumulative we may have an error of several per cent, which I am safe in stating we cannot determine in the ordinary way. If we have two or three different kinds of errors, any one of which amounts to over one per cent, we are getting into very serious condition. It is no uncommon thing in the present state of or business to have bills running about fifteen or twenty thousand dollars monthly. When there is an error of two or three per cent, it is a very serious matter. I don't think the ordinary meter tester is capable of making an accurate test involving the current transformer and the potential transformer. The apparatus would be too bulky to carry around. I think it is necessary for some one to take up the subject from a practical standpoint and make these tests, which have been made at laboratory—make them under practical conditions.

W. A. Hillebrand: I have only one thing to say, and that is with reference to Mr. Lamme's remark about the effect of the power factor on the capacity of the converter, especially in the heating of the coils near the point at which the tap is brought out. Mr. Charters and I spent about three months last year investigating the behavior of induction and synchronous motors under various conditions. These were small machines, to be sure, not over 10 h.p. at most, but they showed the power factor to be extremely sensitive to even slight variations in either amount or phase relation of the applied electromotive forces; much more sensitive than might be expected from the inconsiderable current unbalance that occurs under these conditions.





General view of Great Northern three-phase locomotive

[Hutchinson]

A paper presented at the 240th meeting of the American Institute of Electrical Engineers New York, November 12, 1909.

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THE ELECTRIC SYSTEM OF THE GREAT NORTHERN RAILWAY COMPANY AT CASCADE TUNNEL

BY CARY T. HUTCHINSON

The first three-phase installation on a trunk line railway in the United States was put into operation early in July of this year at the Cascade Mountain tunnel on the Great Northern Railway, in the State of Washington, about one hundred miles east of Seattle.

I purpose in this paper giving a general description of the plant with especial reference to the electric locomotives, together with a brief statement of its operation for the short period since it has been put into service; this record will of necessity be somewhat sketchy, as there has not been sufficient time to accumulate full data for the various conditions of operation that will be met with in service, especially the performance during winter.

In general the plant comprises a hydroelectric generating station, operating under a head of 180 ft., having a capacity of approximately 5000 kw. in generators at 6600 volts and 25 cycles; a transmission system operating at 33,000 volts, delivering energy to a sub-station where it is transformed to 6600 volts, at which pressure it is supplied to the overhead conductors and to the locomotive by way of an overhead trolley; on the locomotive the pressure is reduced by three-phase transformers to 500 volts for the supply of the four three-phase motors with which each locomotive is equipped.

The Great Northern Railway crosses the Cascade Mountains through a tunnel 13,873 ft. long; this tunnel is on a tangent and has a uniform gradient of 1.7 per cent; rising to the tunnel from Leavenworth, on the east, the ruling grade is 2.2 per cent, and

21 per cent of the total distance of 32.4 miles from Leavenworth to the tunnel is on the ruling grade. From Skykomish on the west to the summit the ruling grade is 2.2 per cent, and 44 per

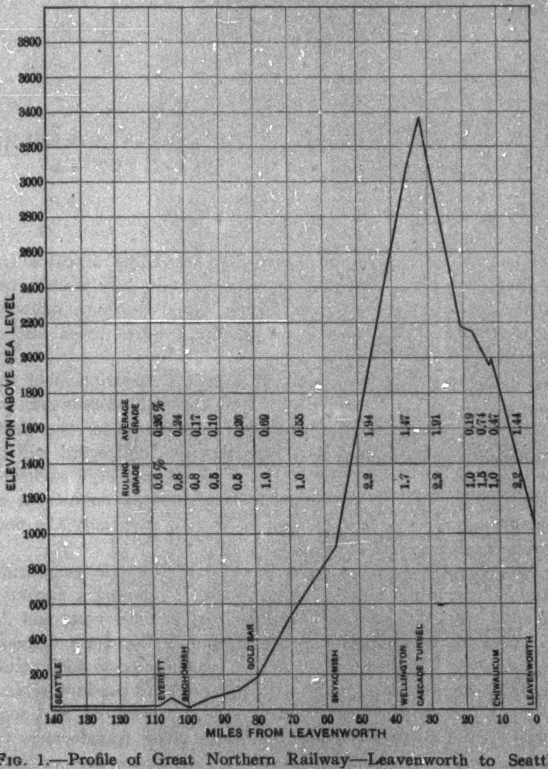


FIG. 1.—Profile of Great Northern Railway—Leavenworth to Seattle

cent of the distance of 24.8 miles is on the ruling grade. Fig. 1 shows a condensed profile of this section of the road; the average up grade from Skykomish to Wellington is 1.94 per cent and from Leavenworth to Cascade, 1.37 per cent.

The operation of the tunnel with steam locomotives was at all times difficult and frequently very dangerous on account of the heat and smoke from the locomotives. Crows Nest coal, which is exceptionally free from sulphur and gas-forming materials, was used for the tunnel service. It was the custom to clean the fires of each locomotive and to put on just sufficient coal to carry it through the tunnel. In the tunnel the rails became very wet from condensed steam, and were frequently covered with a layer of coal soot and ground sand, making them very slippery. The temperature in the locomotive cab was almost unbearable, rising at times as high as 200 deg. fahr. Under ordinary circumstances it required from twenty minutes to an hour for the tunnel to clear itself of gases, but on days when the wind was changeable, the passage of the gases from the tunnel would be stopped by the change in the direction of the wind, and they would pocket. Under such circumstances, work in the tunnel was very dangerous. There are refuge chambers containing telephones every quarter of a mile, but it was a difficult matter to keep these instruments in order, on account of the gases, smoke, and moisture.

The tunnel is lined with concrete throughout its length, and is in good condition. The roof is practically dry. The entire tunnel drips more or less from condensed steam just after the passage of a train, but is comparatively dry at other times. The temperature changes at the top of the tunnel are very rapid, varying from atmospheric temperature to several hundred degrees fahr. from the heat of the locomotive exhaust. For these reasons this tunnel is the limiting feature to the capacity of the Great Northern Railway for hauling freight across the mountains.

Mallet compound engines are used on this division, one at the head of the train, and one pushing. The mountain section as a whole also fixes a limit to the capacity of the road, on account of the slow speed necessitated by heavy traffic; it is impossible for steam locomotives to haul heavy trains on the mountain at a greater speed than seven or eight miles per hour.

The plant described herein is designed for use over the entire mountain division, by extending the system of conductors and building additional stations; it was not designed for the operation of the tunnel alone, although even if the problem had been the handling of the traffic through this tunnel and its approaches only, the three-phase system would in all probability have been selected, on account of its greater simplicity and less cost. The choice of the system to be used was under consideration for more than a year; the three-phase system was finally decided on, plans were prepared, bids obtained, and the contract for the four locomotives let on June 22, 1907.

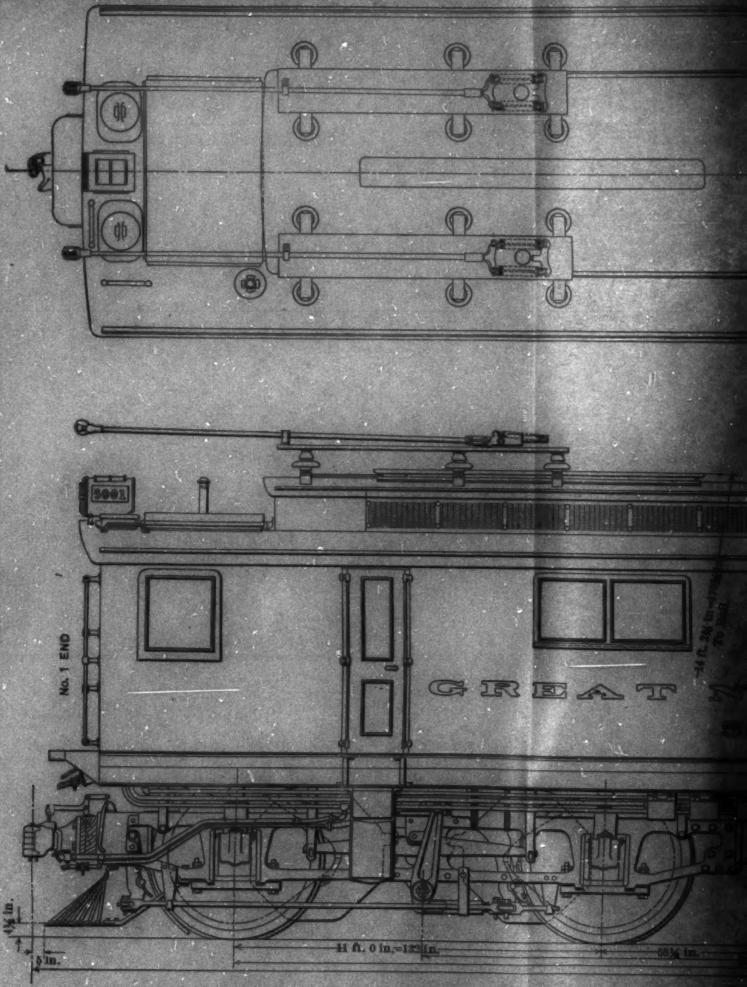
The original problem was to provide equipment to handle a train having a total weight of 2000 tons, excluding the electric locomotives, over the mountain division from Leavenworth to Skykomish, a distance of 57 miles. The system was to be first tried out at the Cascade Tunnel.

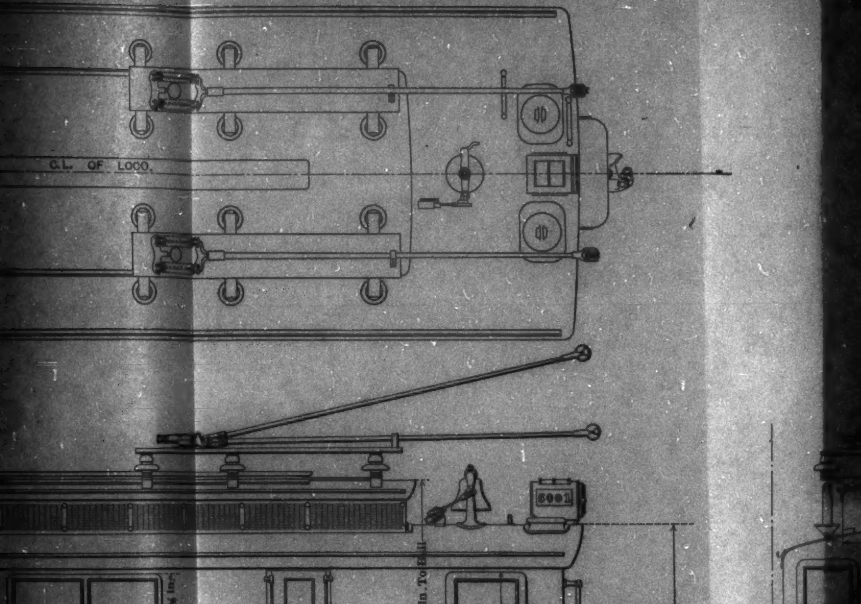
The tractive effort required to accelerate a train having a total weight of 2500 tons on a 2.2 per cent grade, using 6 lb. to the ton for train resistance and 10 lb. to the ton for acceleration, making a total of 60 lb. to the ton, is 150,000 lb.; this would require four locomotives of a tractive effort of 37,500 lb. each. The railway company's engineers limited the weight on a driving axle to 50,000 lb.; therefore four driving axles per locomotive are needed, giving a coefficient of adhesion of about 19 per cent. This is a measure of the maximum power required. The locomotive was, therefore, designed to give a continuous tractive effort of approximately 25,000 lb., and it was expected that four would be used with a train maximum weight. But the locomotive as built greatly exceeds this specification.

GENERAL DESIGN OF LOCOMOTIVE

The locomotive as built is shown in Fig. 2. The principal data of locomotive are as follows: total weight 230,000 lb. all on drivers; two trucks connected by a coupling, each truck having two driving axles; a three-phase motor connected by twin gears to each axle; gear-ratio, 4.26; diameter of driving wheels 60 in.; synchronous speed of motor 375 rev. per min. giving a speed of 15.7 miles per hour at no load, dropping to 15 miles per hour for a load corresponding to the one-hour rating. The motors are wound for 500 volts and are completely enclosed and air-cooled; clearance between stator and rotor, ⅛ in.; trolley pressure, 6000 volts; each locomotive has two three-phase transformers reducing the pressure from 6000 to 500 volts, arranged with taps so that 625 volts may be used on the motor.

The distribution of the total weight of the locomotive is as follows:


3001
No. 1 END
GREAT
11 ft. 0 in.=132 in.
68¼ in.
4½ in.
5 in.


C.L. OF LOCO.
5001
THERN
2 ft. 2½ in.
4 ft. 10 in.
24 in.
14 ft. 0 in.=168 in. To Bell
2 ft. 6 in.
33½ in.
No. 2 END
142 in.
6 in.
5 ft. 11 in.
24 in.
22 in.
87½ in.
54½ in.
22 in.
11 ft. 0 in.=132 in.
31 ft. 9 in.
"B" SIDE
48½ in.
30 in.
20½ in.

al dimensions of Great Northern three-phase locomotive.

2 Trucks	81,500 lb.
1 Cab	30,000 "
4 Motors	48,800 "
8 Gears and gear cases	11,000 "
2 Transformers	20,800 "
2 Air compressors	5,800 "
1 Blower	1,300 "
40 Rheostats	10,200 "
56 Contactors	3,200 "
Miscellaneous	17,400 "
Total	230,000 lb.
That is,	
Total weight per axle	57,500 "
Dead weight per axle	18,500 "

The specification of the motor required an output of 250 h.p. continuously for three hours with 75 deg. cent. temperature elevation, when supplied with not more than 2000 cu. ft. of air per minute. The test results of the motor show a continuous output of 375 h.p. at 500 volts with 1500 cu. ft. and 400 h.p. at 625 volts, with the same air; the one-hour rating of the motor at 500 volts with 1500 cu. ft. of air per minute is 475 h.p.; the ratio of continuous output to the hour-rating with 1500 cu. ft. of air is therefore 79 per cent. The continuous output at 500 volts corresponds to a tractive effort of 9350 lb. per motor and the one-hour output to a tractive effort of 11,900 lb. per motor; the locomotive will, therefore, give 37,400 lb. tractive effort in continuous duty, or 47,600 lb. tractive effort for one hour. Fig. 3 shows the characteristic curves of the motor, at 500 volts.

Calculations from the profile of this section give:

Westbound, Leavenworth-Cascade	
Average up-grade	1.37 per cent
Distance	32.4 miles
Work per ton at the wheel rim	2.15 kw-hr.
Average power per ton at the wheel at 15 miles per hour	1.00 kw.
Eastbound, Skykomish-Cascade	
Average up-grade	1.88 per cent
Distance	24.8 miles
Work per ton at wheel rim	2.16 kw-hr.
Average power per ton at wheel rim at 15 miles per hour	1.31 kw.
Average power per ton at wheel at 15 miles per hour for round trip	1.12 kw.
Maximum power per ton accelerating on 2.2 per cent grade	1.8 kw.

These figures assume the train to be moving continuously and are based on 6 lb. per ton train resistance, as are all calculations herein unless otherwise stated.

The average power of the locomotive when pulling will then be 1.12 kw. per ton, and therefore each motor can carry 250 tons in continuous service on this mountain division, assuming there are no stops and no opportunity for cooling; or each locomotive could haul (4 ×250 - 115) = 885 tons trailing load, if the power requirements were continous; as there are necessarily stops, the rating as determined by heating is somewhat greater than this.

The locomotive has been tested to a maximum tractive effort of nearly 80,000 lb., corresponding to a coefficient of adhesion of nearly 35 per cent; with 60,000 lb. or 26 per cent, each locomotive can accelerate the train of 885 tons trailing on a 2.2 per cent grade, using 60 lb. per ton as the total tractive effort; or, in other words, the train that a locomotive can haul, as determined by the average duty and safe heating limits, is just about equal to the train that it can accelerate on the maximum grade; that is, the average capacity of the locomotive and its maximum capacity are in the same proportion as the average duty and maximum duty. The design is well balanced.

Making some allowance for these figures for the sake of conservatism, the rating of the locomotive on this division can be put at 750 tons trailing load.

Electric Equipment of Locomotive

Each locomotive is equipped with four three-phase induction motors, wound for 500 volts at the primary or stator; the motors are completely enclosed and are cooled by forced air circulation from a large blower. They are suspended from the axles in the standard manner, except that they are geared at both ends of the armature shaft; this was made necessary by the low speed and high torque required, as it was not considered safe to use a single pair of gears. The gear had 81 teeth, the pinion 19 teeth, giving a gear ratio of 4.26. The gears are of specially hardened steel; in order to secure perfect alignment the two pinions on each shaft were cut simultaneously. At first it was the intention to use some form of spring connection between motor and driving wheel, but this was subsequently abandoned, as it seemed that there would be sufficient flexibility in the armature shaft to take out any small differences between the two sets of gears. As far as can be told at present, this assumption appears to be correct, for there has been no difficulty with the gears and no unequal wear. The gears run with little noise and the construction seems satisfactory.

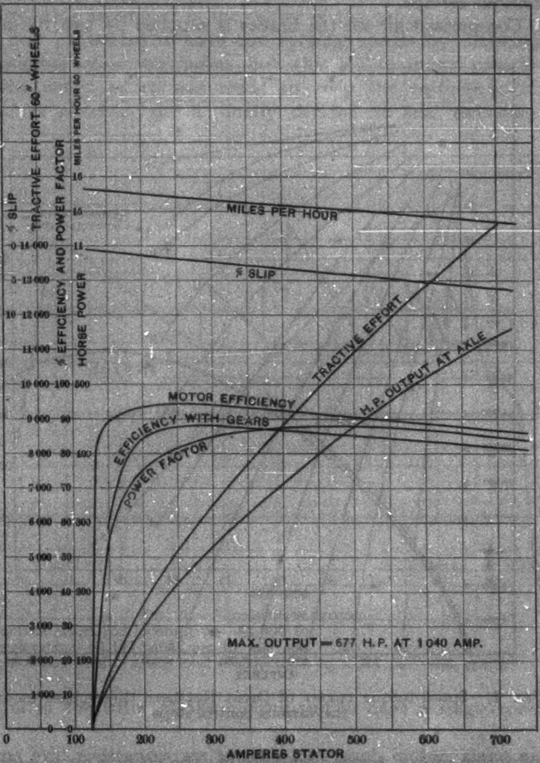


FIG. 3.—Characteristic curves of Great Northern three-phase 475-h.p. 25-cycle, 500-volt motor—gear ratio 4.26; 60-in. wheel

The locomotive carries two three-phase air-blast transformers, having a nominal rating of 400 kw. each, transforming from 6000 volts to 500 volts normally, or to 625 volts by the use of taps. The continuous capacity of the transformer is not as great as that of the motors, although it is fully up to the specification, and it may be that the quantity of air to the transformer will have to be increased when the locomotives are put in continuous service.

Compressed air for the brakes is supplied by two 100-cu. ft. induction-motor-driven compressors; the cooling air is supplied by a 9400-cu. ft. motor-driven blower. The locomotive is equipped with a combined straight and automatic air-brake system.

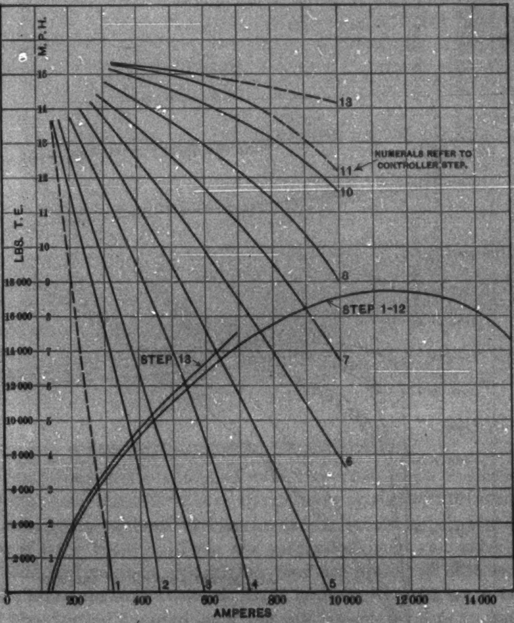


Fig. 4.—Speed-torque curves of Great Northern three-phase motor on the various control steps

Control system. The control system of each motor is separate; the circuits branch from the transformer and are independent through the resistances. There are 14 contactors in each motor circuit, 56 in all. The pilot control is in duplicate, one switch at each end of the locomotive. There is a clear aisle on each side of the locomotive from end to end, all of the apparatus being assembled in the center of the cab.

At first I intended to have two running speeds by changing the number of motor poles, but this led to many complications; every effort was made to keep the equipment as simple as possible, and I finally decided to use resistance control in the rotor of the motors and to have a single-speed unit.

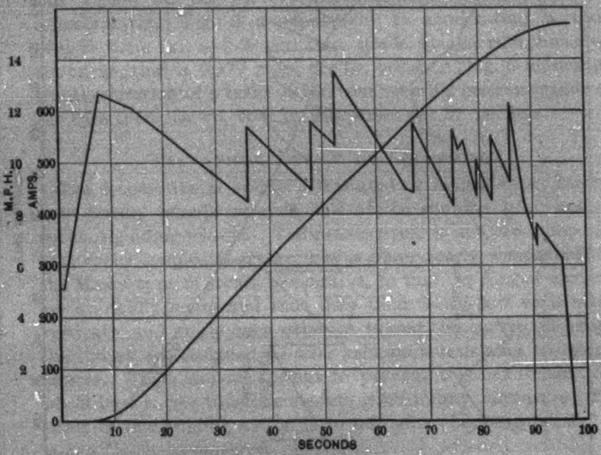


FIG. 5.—Acceleration curves
Tractive effort for locomotive—44,400 lb.
Acceleration—0.177 miles per hr. per sec.
Equivalent to a trailing load of 555 tons on a 2.2 per cent grade

Iron grid resistances are provided for each motor; there are thirteen steps in the control, but in order to reduce the number of contactors to the lowest possible point an unsymmetrical system is used. A change is made in the resistance of one phase only, in passing from step to step. This arrangement in effect treats the three-phase circuit as a single-phase circuit; on each step of the control the torque is the average of the three values of the torque of the separate circuits. The principal advantage of this is that 56 contactors do the work that would otherwise require 128, thus effecting a great gain in the simplicity of the control apparatus.

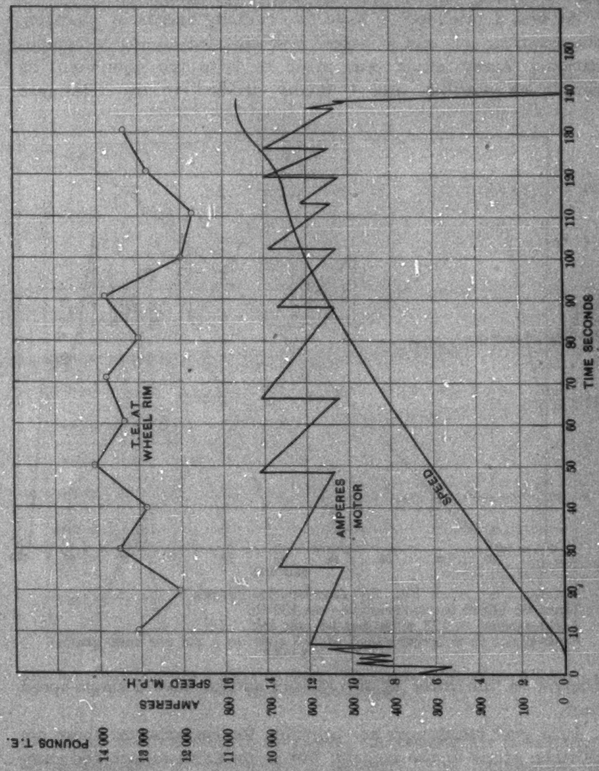


FIG. 6.—Acceleration curves
Tractive effort for locomotive—52,000 lb.
Acceleration—0.12 miles per hr. per sec.
Equivalent to a trailing load of 735 tons on a 2.2 per cent grade

Experience with the locomotive in service indicates that the initial torque, which is approximately 20,000 lb., is somewhat high, and I am now having the control changed so that on the first step two motors only will be thrown in circuit, and on the second step all four motors. This change is readily made by eliminating step 12, which tests have shown to be of little or no value. Fig. 4 shows the speed and tractive effort of the motor on the different control steps, with unbalanced circuits, and on the final step, without resistance.

Many acceleration tests were made at Schenectady, generally using one motor. Fig. 5 shows the result of one of these tests, in which the average tractive effort was 11,100 lb. per motor, corresponding to 44,400 lb. for the locomotive. Fig. 6 shows a similar test in which the average tractive effort was 13,000 lb. per motor, corresponding to 52,000 lb. for a locomotive. Fig. 5 is equivalent to accelerating a train of 555 tons on a 2.2 per cent grade at the rate shown on the curve; that is, 0.177 miles per hr. per sec. Fig. 6 represents the acceleration of a train of 735 tons on a 2.2 per cent grade at the rate there shown, that is, 0.12 miles per hr. per sec.

Mechanical Design of Locomotive

The locomotive is of the articulated or hinged type, having four driving wheels on each half of the running gear and is without guiding wheels. The running gear is not two independent trucks coupled together, but is more nearly comparable to the Mallet type of steam locomotive, in that the hinged sections are so rigidly connected that they tend to support each other vertically and guide each other in taking the curves, although the hinges are designed to offer minimum resistance to lateral flexure. There are no springs to prevent this flexure, and the wheel base is free to accommodate itself to any curvature; the effect of this guiding action is to minimize the flange wear, as in the Mallet locomotive.

The equalization system takes advantage of the vertical rigidity of the truck to distribute the spring stresses over groups of springs instead of concentrating them on single springs; the truck section on the one end is side equalized, but the section on the other end is carried on a three-point suspension. The springs are thereby equalized in groups and the groups are so arranged as to eliminate all skew or twisting stresses in the truck frame.

The framing of the running gear is of substantial steel castings annealed and held together by body-bound taper bolts in reamed holes. Side-frames are castings of truss pattern; end-frames and bolsters are steel castings of box-girder type; the end-frames and all parts are designed for buffing stresses of 500,000 lb. Bolsters are hollow castings and form part of the air reservoir for the motor ventilation; the air is supplied to the motors through a hollow center pin. The wheels are 60 in. in diameter with removable steel tires 3.5 in. thick. The wheel-centers are steel castings. The gears are shrunk on an extension of the wheel-hub, thus eliminating the torsional stresses from the locomotive-axles. The motors are connected through gears at both ends; that is, they are twin-geared to the driving wheels; this has the advantage of maintaining accurate alignment between axles and armature shaft.

The cab is carried on the trucks through center pins on each bolster, the center pin on one end having a slight longitudinal sliding motion to allow for variation in the distances between truck center-pins in taking curves. The cab extends the entire length of the platform and is made of No. 10 steel plates which carry a monitor that supports the trolley base and has a ventilated opening running through the center and perforated side plates to permit the escape of air from the interior of the cab. The greater part of the control apparatus, the rheostat, the transformers, contactors, etc., is placed in a separate compartment 60 in. wide and 22 ft. long, enclosed by steel partitions extending directly up to the monitor roof. This leaves two open operating spaces at the ends of the locomotive, connected together by two side aisles 30 in. in width. This center compartment is divided into three parts by steel-plate partitions, the middle part contains the high-tension apparatus, including switchboard; the end parts are duplicates, each containing one transformer and the contactors for two of the motors. The rheostats are placed in the monitor at the top of the cab. The air for ventilation, after passing through the transformers, cools the rheostats and then escapes to the atmosphere. Placing these rheostats at the top of the cab has also the advantage of raising the center of gravity of the locomotive, which is nearly 60 in. above the rail head, higher than is usual with electric locomotives.

GENERATING SYSTEM

The energy supply for the locomotive is derived from the Wenatchie River, which flows along the line of the railway for a distance of some 20 miles. The power house is located about 2.5 miles west of Leavenworth. There is a low concrete diverting dam in the river at a point about 12,000 ft. west of the power house, and from this dam a wood-stave pipe of 8.5 ft. interior diameter runs for a distance of 10,908 ft. and continuing this stave-pipe line is a steel-pipe line for a distance of 962 ft. The pipe line has substantially the same gradient as the railway line, and gives a static head at low water of 203 ft. and in ordinary water of about 200 ft. The operating head at rated load is 180 ft.

The crest of the diverting dam is 400 ft. long; it has three head gates, a log sluice, and a fishway. The pipe line ends in a surge tank at the corner of the power house, having a total height of 183 ft. above its foundation. The tank proper is 30 ft. in diameter, and with a storage height of 54 ft. above its hemispherical bottom gives a storage capacity of approximately 38,000 cu. ft.

The pipe line leads directly into the upright pipe of the surge tank, which is 8 ft. in diameter; within the upright pipe is a waste pipe having a diameter of 3 ft. 2 in., extending 7 ft. above the level of the crest of the dam; in the tank the waste pipe is expanded uniformly to a diameter of 7 ft. 6. in, thus affording a circular weir of 23.5 ft. in length.

The power house is designed for three main units and two exciter units. There are now installed in the power house two main units, each turbine rated at 4000 h.p., directly connected to a three-phase alternating-current generator.

The two main units now erected, with the exciter, require approximately 500 cu. ft. of water per second when operating at full load of 8,000 h.p., giving a velocity of flow in the penstock of 8.7 ft. per sec.

The extreme low flow of the river at the dam is estimated to be 380 sec-ft. The small pond formed by the dam has a storage capacity equivalent to 8000 h.p-hr., for a depth of one foot; it is possible to draw the water in the dam down three feet. There are two other power sites in the canyon, each affording a head of 200 ft., available for subsequent developments.

The entire hydraulic installation was designed and constructed under the direction of J. T. Fanning, of Minneapolis.

Electric Equipment of Power House

The electric equipment in the power house at present consists of two main generating units, each for a nominal capacity of 2500 kilovolt-amperes at 375 rev. per min., 6600 volts and

25 cycles; these machines are designed to have very large overload capacity, and operate at a low flux density.

There are two exciter units, each having a nominal capacity of 100 kw. at 750 rev. per min. These units also have a large overload capacity; they frequently carry 150 per cent overload, on account of the very poor regulation of the water wheels. A third unit, identical with the first two, has been ordered.

The power house also contains four transformers for raising the pressure to 33,000 volts, each of a nominal capacity of 833 kw. but guaranteed to operate 100 per cent overload for one hour, with a low rise in temperature. Three of these units are in service, the fourth is kept as a spare.

The switchboard apparatus is of the usual type, having panels for the generators and the feeders, and is provided with the usual measuring instruments.

One reason leading to the use of the three-phase system was the possibility of regeneration; that is, of returning energy to the system on down grades. With the present installation it is obviously not possible to make any use of the energy so returned, but in order to prove this practically an automatic rheostat controlled by the speed of generator was installed in the power house; when a train on the down grade reaches a little more than the synchronous speed, the electrodes of the water rheostat are automatically lowered by an amount proportional to the difference between synchronous speed and the speed of the generator; this throws a load on the system and acts as a brake to the train. The operation of this apparatus is entirely effectual.

The nominal capacity of parts of this equipment, in particular of the transformers, may seem unusual; but it must be remembered that the plant is intended to operate on a load having extreme fluctuations, the entire load being on for, say, 15 minutes and then off for two or three hours, and consequently the transformers can be made small.

This plant has operated satisfactorily with the exception of certain troubles with the water wheels; in particular, the generators have shown ability to hold their rated pressure under extreme variations of speed, due to the effective control of the Tirrill regulators. The generator fields, designed for 125 amperes, have frequently carried 300 to 350 amperes, and the regulators have held the pressure normal, in spite of fluctuations of 35 to 40 per cent in speed.

TRANSMISSION LINE

The transmission line extends from the power house at Leavenworth to the sub-station at Cascade, a length of approximately 30 miles, following the railroad all the way; part of the distance it is on the same side of the river as the railroad and part on the opposite side. Figs. 7 and 8 show the general appearances and the details of the construction of the line.

FIG. 7.—General view of transmission line

The line carries two circuits each of No. 2 B. & S. gage stranded hard-drawn copper wire; each circuit is in a vertical plane at one side of the pole, thus permitting the use of short cross-arms; the upper cross-arm was placed some distance below the top of the pole in order to leave room for a ground wire, which has not as yet been installed. The poles are 40 ft. long, placed 6 or 7 ft. in the ground, the tops being 10 in. to 12 in. in diameter; these poles

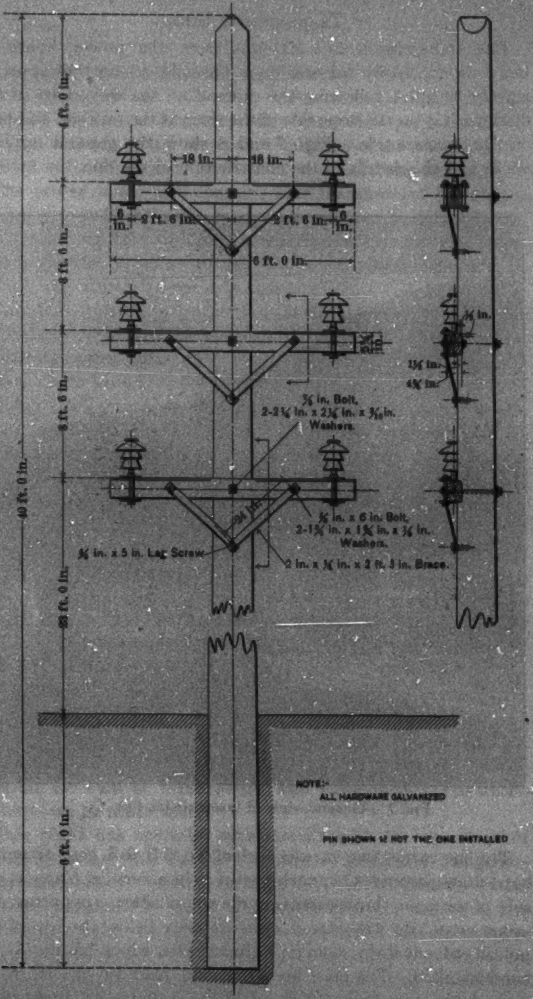

4 ft. 0 in.
18 in.
18 in.
6 in.
2 ft. 6 in.
2 ft. 6 in.
6 in.
6 ft. 0 in.
3 ft. 6 in.
3¾ in.
⅜ in.
1¾ in.
4¾ in.
3 ft. 6 in.
⅝ in. Bolt,
2-2¼ in. x 2¼ in. x 3/16 in.
Washers.
40 ft. 0 in.
24 in.
⅝ in. x 6 in. Bolt,
2-1¾ in. x 1¾ in. x 3/16 in.
Washers.
⅜ in. x 5 in. Lag Screw
2 in. x ⅜ in. x 2 ft. 3 in. Brace.
23 ft. 0 in.
NOTE:-
ALL HARDWARE GALVANIZED
PIN SHOWN IS NOT THE ONE INSTALLED
6 ft. 0 in.

FIG. 8.—Standard pole of transmission line: two 33,000-volt circuits of No. 2 B. & S. gage wire

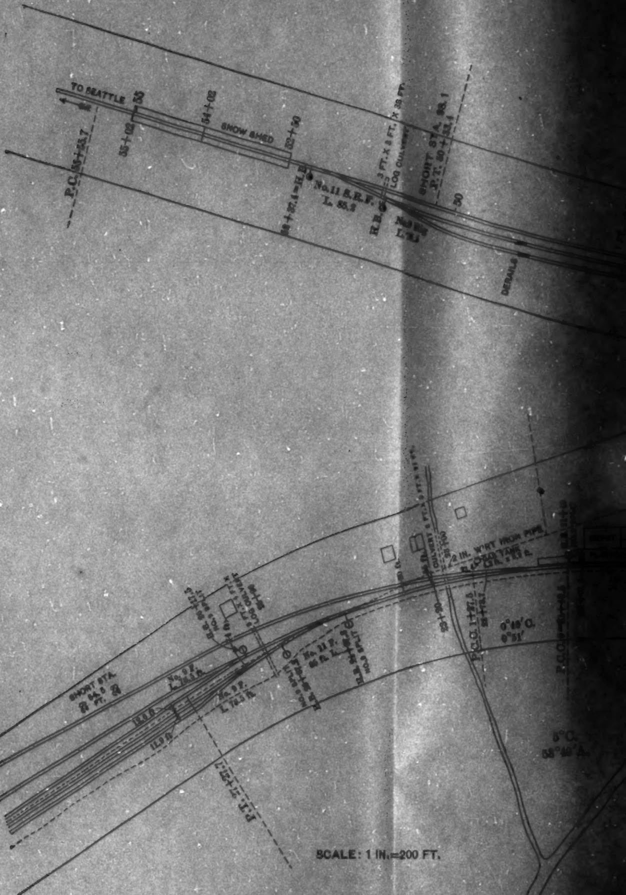
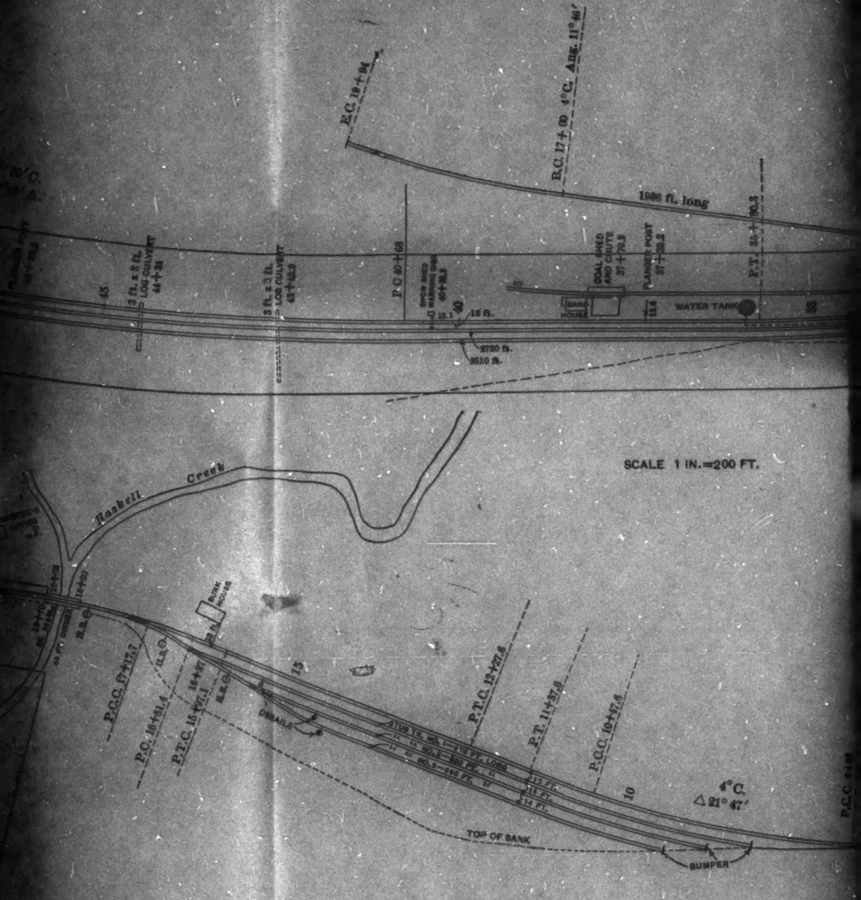

TO SEATTLE
P.C. 56+53.7
55+02
55
54+02
SNOW SHED
52+50
No. 11 S.R.F.
L. 85.2
H.B.
3 FT. X 3 FT. X 38 FT.
LOG CULVERT
SHORT STA. 98.1
P.T. 50+33.4
50
DERAILS
SHORT STA.
FT.
No. 9 F.
No. 9 F.
P.T.
P.C.C.
0°49′ C.
0°51′
2 IN. W'RT IRON PIPE
5° C.
58°40′ A.
SCALE: 1 IN.=200 FT.

Fig. 9.—Plan of Wellington yard showing


B.C. 19+94
B.C. 17+00 4°C. Ang. 11°46′
1986 ft. long
P.T. 35+90.3
45
3 ft. x 2 ft. LOG CULVERT 44+31
3 ft. x 3 ft. LOG CULVERT 42+42.9
P.C. 40+68
SNOW SHED WARNING SIGN 40+38.3
40
12.1
16 ft.
2720 ft.
2610 ft.
SAND HOUSE
COAL SHED AND CHUTE 37+70.9
FLANGER POST 37+38.2
12.6
WATER TANK
35
SCALE 1 IN.=200 FT.
Haskell Creek
BUNK HOUSE
40 FT. GIRDER
P.C.C. 17+17.7
P.C. 16+51.4
P.T.C. 15+97.1
16+47
15
DERAILS
STUB TR. NO. 1—670 FT. LONG
" " NO. 2—500 FT. "
" " NO. 3—640 FT. "
P.T.C. 12+27.6
P.T. 11+37.8
P.C.C. 10+47.8
13 FT.
13 FT.
14 FT.
10
4°C.
△21° 47′
TOP OF BANK
BUMPER

track through the snow shed and two side tracks are electrified. Total length of track electrified, al

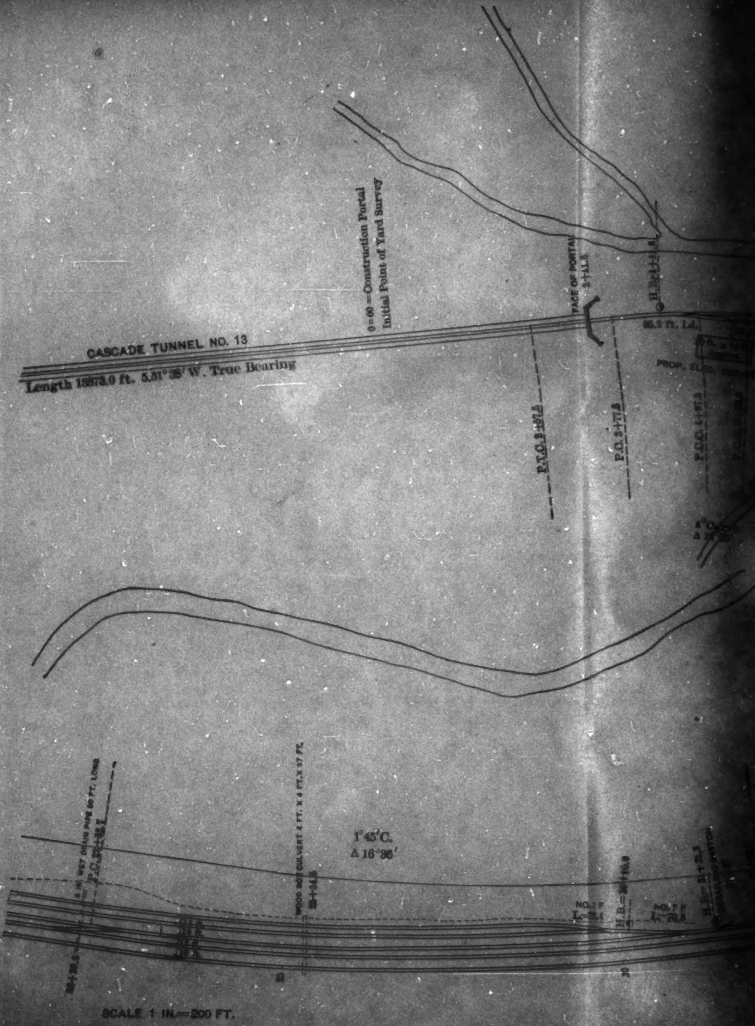
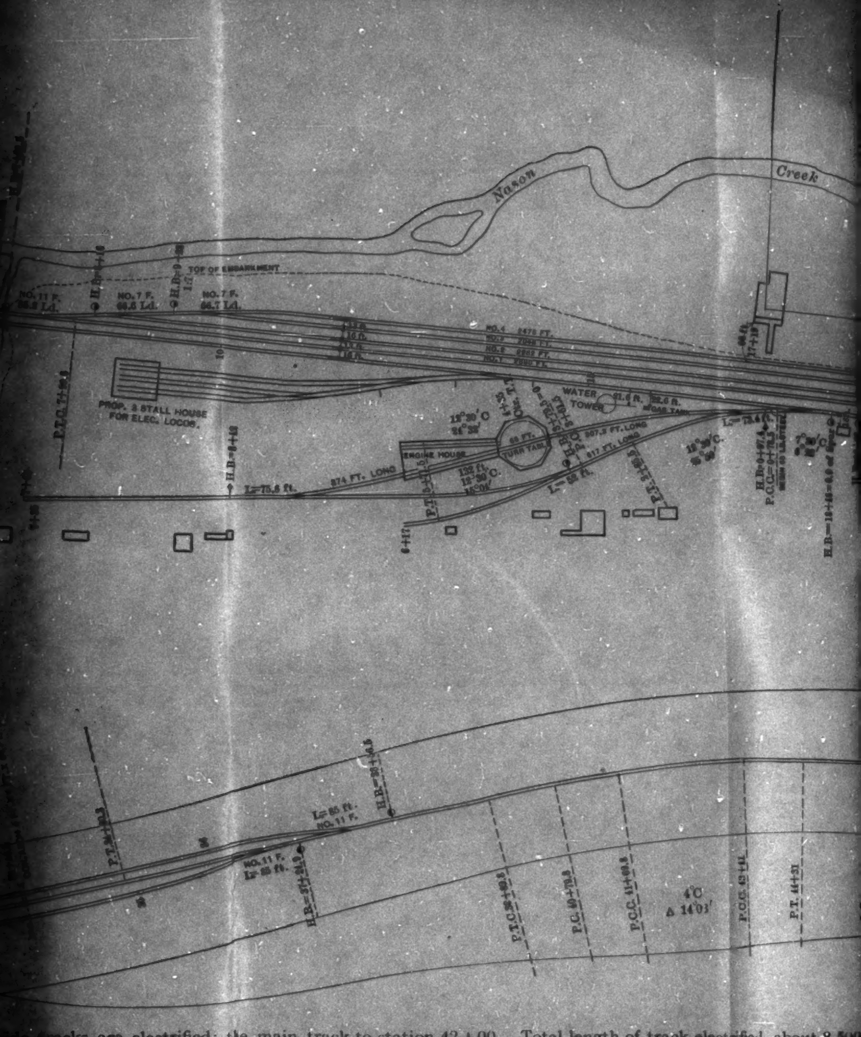
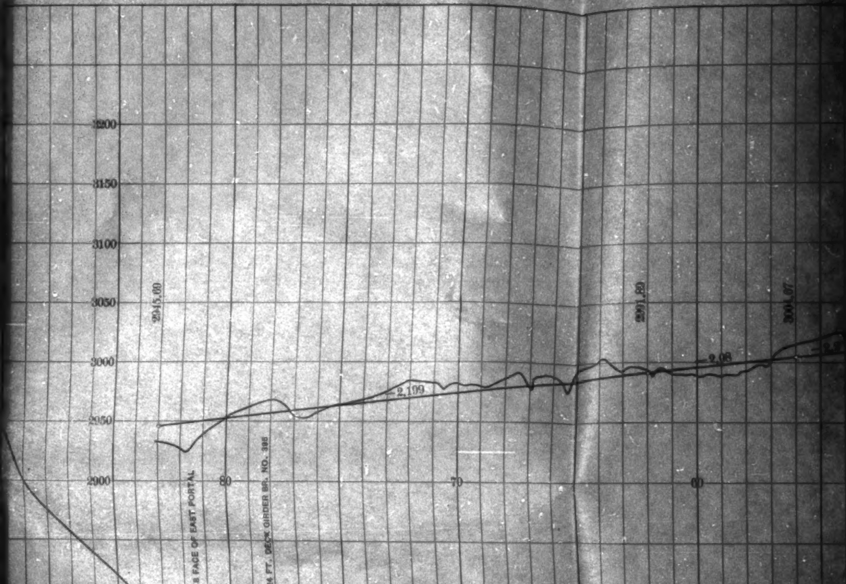
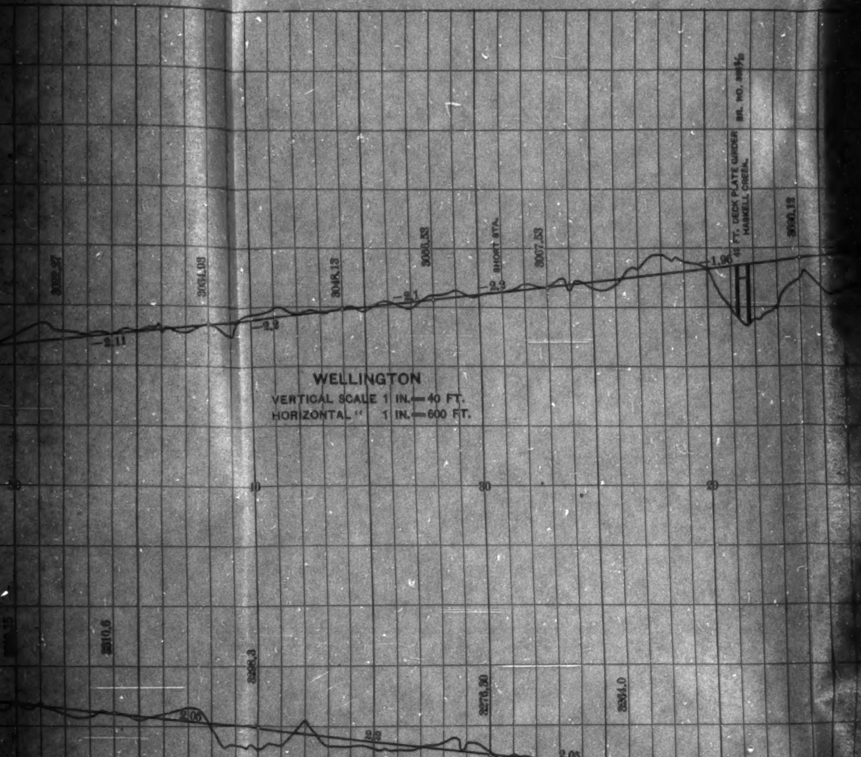

CASCADE TUNNEL NO. 13
Length 13873.0 ft. S.51°38' W. True Bearing
0+00 = Construction Portal
Initial Point of Yard Survey
FACE OF PORTAL
3+11.8
H.B.=4+31.8
36.2 ft. Ld.
PROP. ELEC.
P.T.C. 2+87.5
P.C. 3+77.5
P.C.C. 4+97.5
1°45'C.
Δ 16°36'
6 IN. WET DRAIN PIPE
P.C.
WOOD BOX CULVERT 4 FT. X 4 FT. X 37 FT.
25+54.5
25
30
NO. 7 F
NO. 7 F
H.B.=
H.B.= 31+
DERAILING SWITCH
SCALE 1 IN.=200 FT.

FIG. 10.—Plan of Cascade yard, showing tracks. The main


Nason Creek
TOP OF EMBANKMENT
NO. 11 F.
NO. 7 F.
66.6 Ld.
NO. 7 F.
66.7 Ld.
NO. 4 2476 FT.
NO. 3 2098 FT.
NO. 2 2262 FT.
NO. 1 2390 FT.
PROP. 2 STALL HOUSE FOR ELEC. LOCOS.
WATER TOWER
21.6 ft.
22.6 ft.
ENGINE HOUSE
TURN TABLE
65 FT.
12°30′C
21°32′
132 ft.
12°30′C.
15°01′
374 FT. LONG
397.3 FT. LONG
317 FT. LONG
L=75.6 ft.
L=73.4 ft.
12°30′C.
H.B.=8+42
6+17
L=85 ft.
NO. 11 F.
NO. 11 F.
L=85 ft.
H.B.=37+24.0
P.T.C.38+82.8
P.C. 40+70.8
P.C.C. 41+69.8
P.C.C. 43+41
P.T. 44+31
4°C
Δ 14°01′

ide tracks are electrified; the main track to station 42+00. Total length of track electrified, about 8,500


3200
3150
3100
3050
3000
2950
2900
2945.60
2991.89
3001.07
−2.109
−2.08
−2.9
80
70
60
3400
3350
3300
3250
3200
3150
3100
3346.5
3348.0
3 + 41.8 FACE OF EAST PORTAL
3351.0
3351.0
NASON CREEK 24 FT. DECK GIRDER BR. NO. 395
3347.4
−0.86
3336.3
CASCADE
0
10
20


3032.27
3034.03
3048.13
3056.53
SHORT STA.
3067.53
45 FT. DECK PLATE GIRDER
HASKELL CREEK.
BR. NO.
3090.12
-2.11
-2.3
-2.1
-2.3
-1.96
WELLINGTON
VERTICAL SCALE 1 IN. = 40 FT.
HORIZONTAL " 1 IN. = 600 FT.
10
20
3310.6
3293.3
3276.30
3254.0
2.05
2.2
2.05
2.2
VERTICAL SCALE 1 IN. = 120 FT.
HORIZONTAL " 1 IN. = 600 FT.
40
50
60
70

11.—Profile of Wellington and Cascade yards.

are unusually sturdy, and it was owing to the fact that timber of this kind could be obtained cheaply in the West that this type of construction was adopted. The line is divided into three sections by two out-of-door switches operated by means of a pole deposited with a station agent; each switch is near a station.

In the design of the line, as in all other features of the work, the aim was to secure apparatus and types of construction giving promise of the greatest reliability, in order that there should be as few links as possible in the chain from the power house to the locomotive that would be liable to derangement; for this reason a comparatively low line pressure is used.

The telephone line is carried on the same poles; the transmission line is not transposed. but the telephone line is transposed at every fifth pole.

The construction of this line was completed a year ago, and it has stood through one winter, during which there were more than thirty snow and rock slides; only one of these slides caused damage to the line, and in this case only one of the two circuits was interrupted; it could have been repaired within an hour. The same slide interrupted the operation of the railroad for eight to ten hours.

Substation. The substation is at Cascade, practically at the east portal of the tunnel. Three single-phase transformers are in service and a fourth in reserve; these transformers are duplicates of those in the power house. The equipment of the substation is along the usual lines and calls for no special comment. The low-pressure bus-bars at the substation are connected to the overhead wires in the Cascade yard and also to the Wellington feeder, which runs through the tunnel to the extreme end of the Wellington yard.

Tracks electrified. Fig. 9 and 10 show plans of the two yards. In both yards the main track and two side tracks are electrified, together with the necessary crossovers, etc. The total length of the track equipped, including the tunnel, is about six miles. Fig. 11 shows profile of the yards; the tunnel grade is 1.7 per cent.

The length of the several parts of the overhead structure is as follows:

Substation to east portal of tunnel	200	ft.
East portal to west portal	13,900	"
West portal to end of electrified track	6,960	"
Total, substation to rear electric locomotive	21,060	"

or, practically 4 miles.

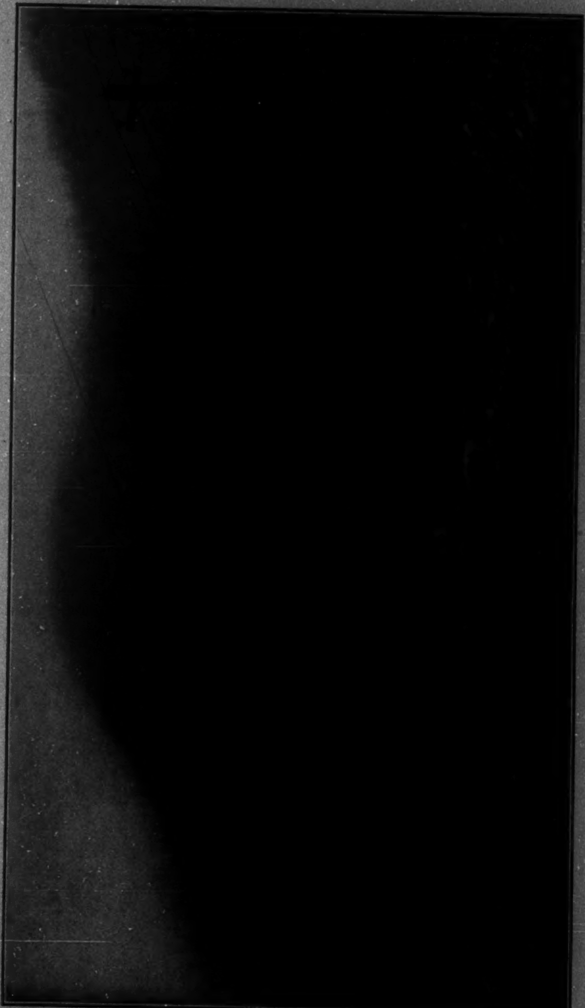


Fig. 12.—Overhead construction in Cascade yard, showing bracket construction at curve

OVERHEAD CONSTRUCTION IN YARDS

Figs. 12, 13, 14, 15 and 16 show the general type of bracket and cross-catenary construction used in the yards. Figs. 17, 18 and 19 show details of the cross-catenary suspension. Fig. 20 shows details of the bracket construction. The wires are 24 ft. above top of rail and 5 ft. apart; for single tracks a bracket type of construction is used, and for multiple tracks a cross-catenary type, supported by very heavy wooden poles located about 8 ft. from center-line of outer tracks, thus leaving unobstructed the space between adjacent tracks. The wires are supported at intervals of 100 ft.

Multiple track supports consist, for each phase, of a steady span supported by and insulated from a cross-catenary span, both spans being secured to cross-arms on the poles by means of porcelain petticoat strain insulators; the spans for the two respective phases are three feet apart. The wires of the same phase, for the different tracks, are insulated from each other by means of wood breaks and porcelain link insulators, in series.

In the case of brackets, each phase is insulated from ground by means of a wood break in series with a porcelain petticoat strain insulator.

Where wires of opposite phases cross at turn-outs, they are insulated from each other by section insulators made of wood and about five feet in length; four insulators are used, each connected at one end to a special 8-deg. crossing pan and at the other end to one of the four wires converging toward the crossing. Except for one track whose wires are cut straight through the crossing pans without section insulators, it is necessary to switch the controller to the off position when the trolley wheel passes under the insulators; methods of avoiding this have been considered and are being tried out.

Heavy steel bridges, Fig. 14, forming anchorages for the trolley wires are located in both yards at intervals of 1000 ft. Lightning protection, though thunder storms are rare, is afforded by arresters connected to the wires at the ends of the tunnel and yards.

Both rails in the tunnel and one rail in the yards are bonded, with cross-bonding at frequent intervals. A single 4/0 exposed bond is used at each joint, having a length of 36 in. in the tunnel, and 36 and 50 in. in the yards.

In my opinion the use of double insulation everywhere is the reason for the almost total freedom from troubles of any

Fig. 12—Cross-catenary construction in Wellington yard at switch point

kind originating on the overhead structures; two separate pieces of insulation of any given strength are much better than one piece of four times that strength. The only troubles experienced up to the present have been at the section breaks and turn-outs, and have been caused by the trolley wheel leaving the wire. There has been no failure of the wires at any point of the overhead structure nor any breakdown of insulation.

OVERHEAD CONSTRUCTION IN TUNNEL

This construction is shown in Fig. 21, 22 and 23. Fig. 21 gives a cross-section of the tunnel and shows the location of the trolley wires, trolley feeder, the wires for the lighting circuits, and the telegraph and telephone cable. Fig. 22 shows a cross-section of the method of supporting the trolley wires, and Fig. 23 shows a longitudinal view of the trolley suspension scheme; this, however, does not show the swiveled connection of the stud to the clamp holding the trolley wire at the lower end. The necessity for adding this swivel connection was shown by the breakage of several studs.

In the tunnel the wires are 17 ft. 4 in., above the top of the rail and 8 ft. apart; the latter spacing enables train-men to operate the hand-brakes, or walk on the tops of freight cars, the construction being such that head-room in not interfered with. Each wire is supported every 50 ft. by means of a 14-in. Detroit clamp attached by swiveled connection to a stud which is in turn swiveled to the middle point of a turnbuckle. The two eyes of the latter, by means of strand wire, connect each to a link and petticoat strain insulator arranged in series, the two petticoat insulators being secured to the roof of the tunnel by means of two expansion bolts, about 5 ft. 6 in. apart. Anchors and side-braces for the wires in the tunnel are located at intervals of 3000 ft.

Practically all metal work in the tunnel supports is copper or bronze, but experience has shown that galvanized iron, soon becoming protected by a slight coating of soot, would have been satisfactory. The insulators, when first put in service, were covered by a very thick coating of wet soot, but, even under these conditions, it was found possible gradually to bring the voltage up to normal without breakdown. Volumes of smoke and steam issuing from steam locomotives caused only a slight surface leakage, and one rough cleaning sufficed to put the insulators in reliable working condition.

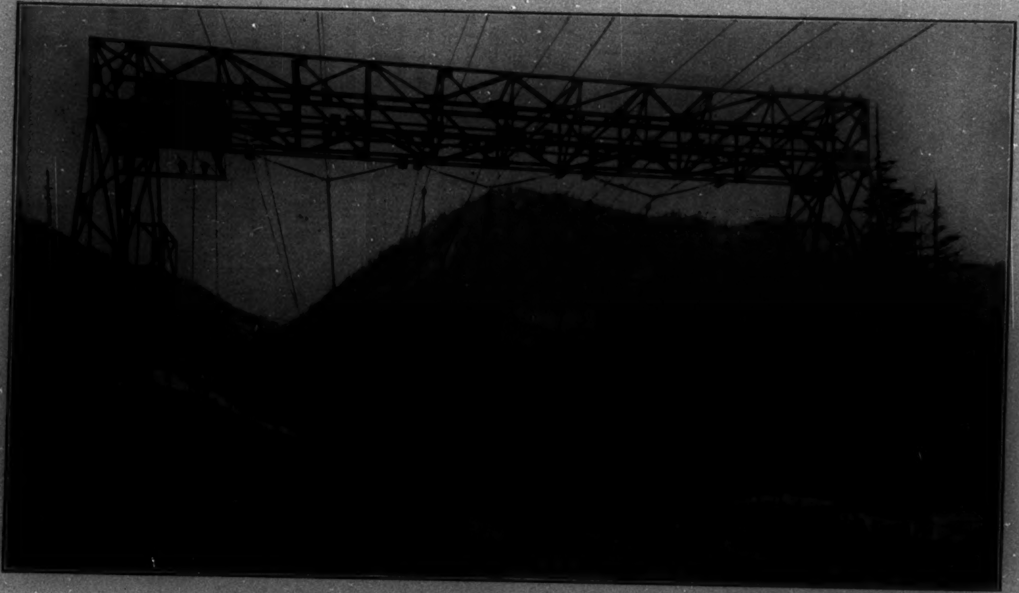


FIG. 14.—Anchor bridge in Wellington yard, showing three tracks electrified

Spacing the wires 8 ft. in the tunnel was necessitated by the requirement of the railroad company that there should be no construction in the roof of the tunnel which could possibly interfere with a brakeman's walking on the top of a freight car. This change in the location of the wires complicated the construction somewhat and was one of the principal reasons leading to the use of a trolley wheel in place of a bow collector. It has, however, caused no material inconvenience and is satisfactory as long as the trolley wheels are in use, but if a change is made to a bow collector, which is not impossible, there may be difficulty in adapting the bow to this location of the wires.

FIG. 15.—Construction at switch point, Wellington yard

Electric lighting. It is intended ultimately to clean and whitewash the tunnel and light it electrically, and for this purpose a lighting system has been installed. Five transformers of 4 kw. capacity each are placed in refuge chambers; incandescent lights are spaced 50 ft. apart and are connected four in series of a 500-volt system. Several plans were worked out for this lighting system, but taking into account maintenance costs, it seemed best to use a standard 110-volt carbon filament lamp.

Telegraph lines. The telegraph wires, ten in number, as shown in Fig. 21 run through the tunnel in a cable; this service was thrown entirely out of commission when the electric locomotives began running. There is no interference with the telegraph wires due to the transmission lines paralleling them for thirty miles; the entire interference seems to originate in the tunnel. In order to eliminate this interference, a neutralizing transformer has been installed and adjustments are now in progress. There has been little difficulty in making the ordinary single-wire telegraph service satisfactory, but considerable difficulty has been experienced in

Fig. 16.—Bracket construction at curve Wellington yard

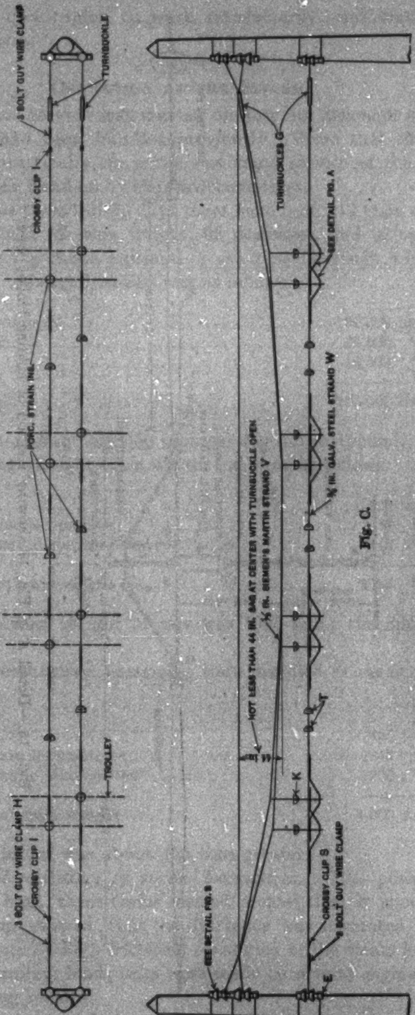

3 BOLT GUY WIRE CLAMP
TURNBUCKLE
CROSBY CLIP I
PORC. STRAIN INS.
TROLLEY
3 BOLT GUY WIRE CLAMP H
CROSBY CLIP I
3 BOLT GUY WIRE CLAMP
TURNBUCKLES G
SEE DETAIL FIG. A
NOT LESS THAN 44 IN. SAG AT CENTER WITH TURNBUCKLE OPEN
1/2 IN. SIEMEN'S MARTIN STRAND V
3/8 IN. GALV. STEEL STRAND W
T
K
CROSBY CLIP S
3 BOLT GUY WIRE CLAMP
SEE DETAIL FIG. B
E
Fig. C.

FIG. 17.—Cross-catenary suspension, general scheme]

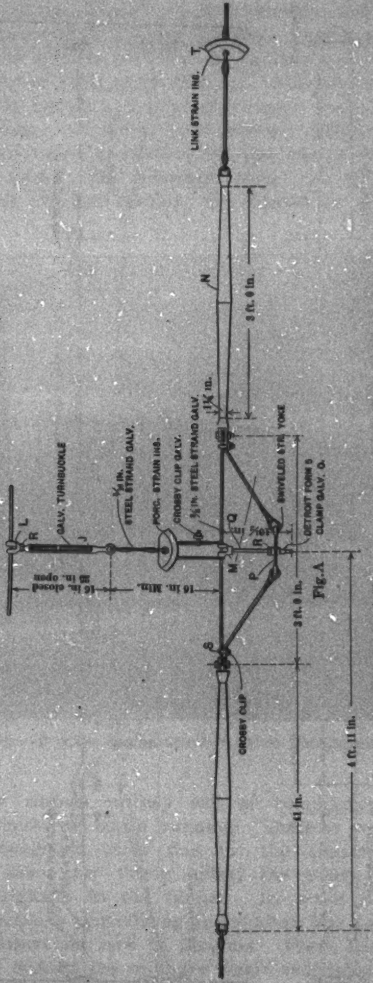

LINK STRAIN INS.
T
N
3 ft. 0 in.
1¼ in.
GALV. TURNBUCKLE
L
R
J
$\frac{5}{16}$ IN. STEEL STRAND GALV.
PORC. STRAIN INS.
CROSBY CLIP GALV.
$\frac{3}{8}$ IN. STEEL STRAND GALV.
Q
M
R
P
S
SWIVELED STR. YOKE
DETROIT FORM 5 CLAMP GALV. O.
16 in. closed 22 in. open
16 in. Min.
3 ft. 0 in.
Fig. A
CROSBY CLIP
41 in.
4 ft. 11 in.

FIG. 18.—Detail *A* of Fig. 17 showing method of holding trolley wire.

getting the quadruplex to work satisfactorily; this matter is still unfinished.

OPERATION OF THE SYSTEM

The electric service was started on July 10, although one or two trains had been handled previously. From that time to August 11, practically the entire eastbound service of the company has been handled by electric locomotives.

During this period of 33 days there have been 212 train movements of which 82 were freight, 98 passenger, and 32 special. In each case the steam locomotive was hauled through with the train. The tonnage handled was as follows:

Freight tonnage	171,000 tons
Passenger "	88,500 "
Special "	15,500 "
Total	275,000 tons

This is an average of 8350 tons per day, all eastbound.

The average freight train weight has been as follows:

Cars	1480 tons
One Mallet locomotive	250 "
Three electric locomotives	345 "
Total train weight	2075 "

The maximum weight of cars was 1600 tons; the minimum 1200 tons.

The representative passenger train handled is made up as follows:

Coaches	426 tons
Two steam locomotives	347 "
Two electric locomotives	230 "
Total train weight	1,003 tons

The maximum was about 125 tons greater.

Frictional resistance of steam locomotives. The power required to haul these trains seemed greater than it should be; investigation showed that the difference was accounted for by the unexpectedly high frictional resistance of the steam locomotves, as a trailing load; tests were made on several engines with the following results:

TABLE III

1 Test No.	2 Engine classification	3 Total weight with tender Tons	4 Weight on drivers Tons	5 Total resistance on 1.7 per cent grade lb.	6 Equivalent weight of freight cars Tons
1	Mallet No. 1904. 2-6-6-2	250	158	19,340	482
2	" No. 1911. 2-6-6-2	250	158	17,500	432
3	" No. 1905. 2-6-6-2	250	158	24,200	602
4	Consolidation.... 2-8-0	159	90	10,080	255
5	Pacific.......... 4-6-0	188	70	10,270	257

The tests were made by towing an engine through the tunnel behind an electric; the electric was fitted up with test instruments and the total tractive effort was thereby obtained. An allowance of 6 lb. per ton was made for the resistance of the electric and the difference is the draw-bar pull in column 5. Column 6 is the equivalent load in cars, taking car resistance as 6 lb. per ton. Each test given is the average from six to twelve separate readings. The average for the three Mallets is more than 20,000 lb.

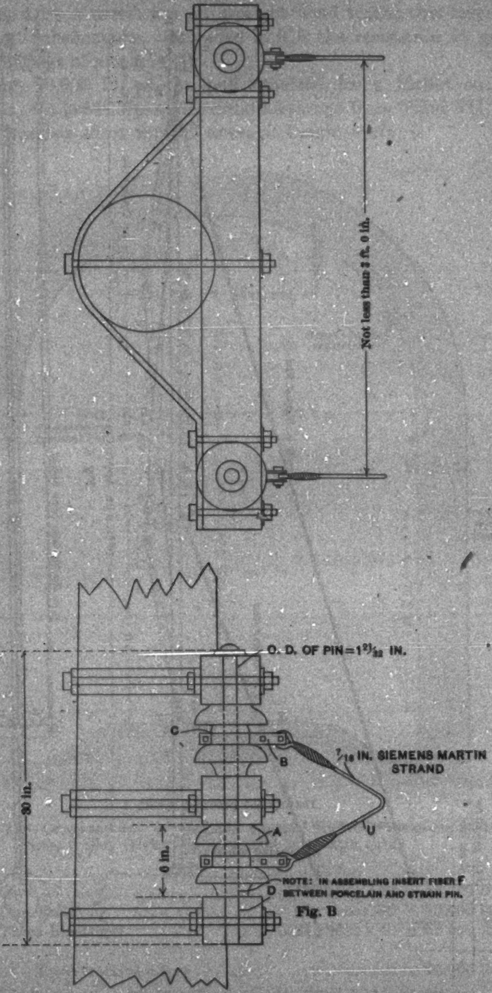
If the grade resistance be deducted from the total pull, and the difference lumped as "lb. per ton" for the locomotive and tender, there results:

TABLE IV

1 Engine classification	2 Frictional resistance of locomotive	3 lb. per ton
Mallet No. 1904.......	10,840 lb.	43.0
Mallet No. 1911.......	9,000 "	36.0
Mallet No. 1905.......	15,700 "	63.0
Consolidation..........	5,480 "	34.5
Pacific...............	3,870 "	20.7
Electric..............	1,500 "	13.0

The average for the three Mallets is 47.0 lb. per ton for the frictional resistance on a straight level track.

The figure for the electric was obtained from tests made by


Not less than 2 ft. 0 in.
O. D. OF PIN = $1\frac{21}{32}$ IN.
C
B
$\frac{7}{16}$ IN. SIEMENS MARTIN STRAND
U
A
D
30 in.
6 in.
Fig. B

NOTE: IN ASSEMBLING INSERT FIBER F BETWEEN PORCELAIN AND STRAIN PIN.

Fig. 19.—Detail *B* of Fig. 17 showing method of attachment of cross-catenary to pole

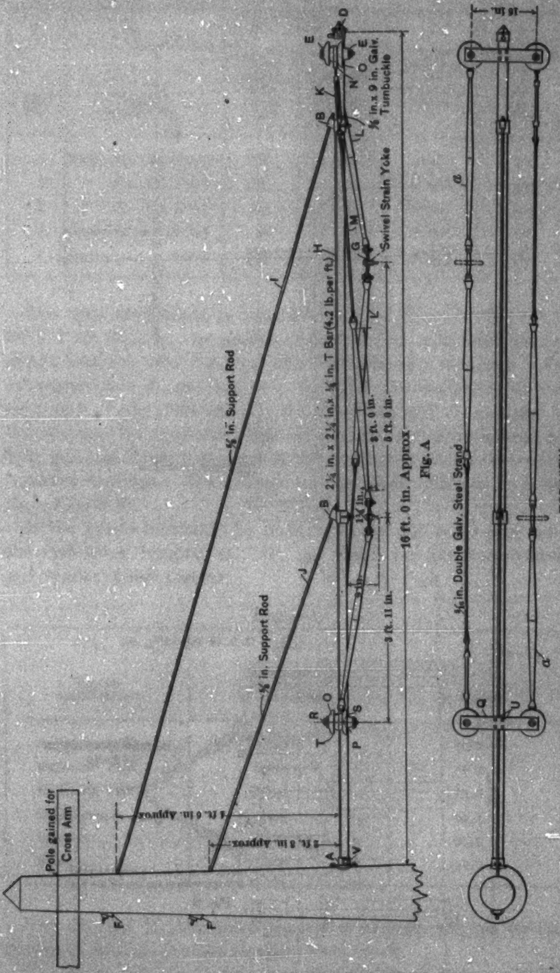
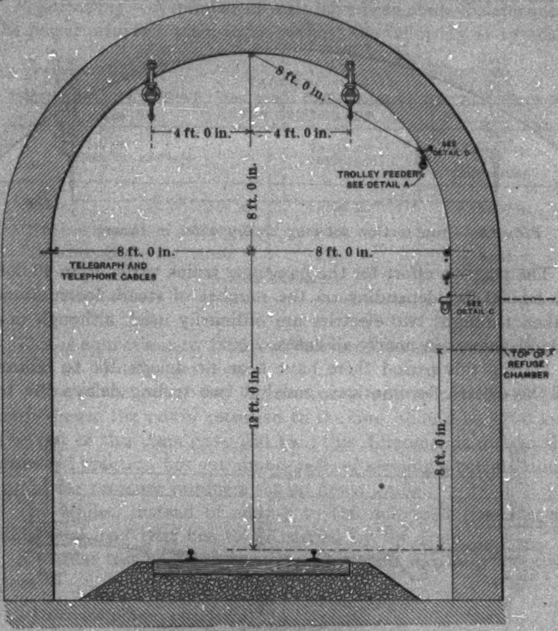

Pole gained for Cross Arm
4 ft. 6 in. Approx
2 ft. 8 in. Approx
A
V
F
F
T
R
O
P
S
⅜ in. Support Rod
J
B
I
⅝ in. Support Rod
H
2¼ in. x 2¼ in. x ¼ in. T Bar (4.2 lb. per ft.)
G
M
Swivel Strain Yoke
L
L
K
B
N
O
E
E
D
⅝ in. x 9 in. Galv. Turnbuckle
3 ft. 11 in.
3 ft. 0 in.
8 ft. 0 in.
8 ft. 0 in.
1¼ in.
16 ft. 0 in. Approx
Fig. A
16 in.
a
5/16 in. Double Galv. Steel Strand
Q
U
a
TOP VIEW

Fig. 20.—Bracket construction in yards

towing it by a motor car on straight level track; this test was made at Schenectady. Included in it is the resistance of gears and bearings of motors.

Using 20,000 lb. as the pull required for a Mallet on the 1.7 per cent grade, the approximate average from Table III, the total tractive effort for the average freight train, is:


8 ft. 0 in.
4 ft. 0 in.
4 ft. 0 in.
SEE DETAIL B
TROLLEY FEEDER SEE DETAIL A
8 ft. 0 in.
8 ft. 0 in.
8 ft. 0 in.
TELEGRAPH AND TELEPHONE CABLES
SEE DETAIL C
TOP OF REFUGE CHAMBER
12 ft. 0 in.
8 ft. 0 in.

CROSS SECTION OF TUNNEL

FIG. 21.—Cross-section of Cascade tunnel, showing location of trolley wires, trolley feeder, lighting and telegraph cable

Cars	1480 tons × 40 =	59,200 lb.
One Mallet	250 tons × 80 =	20,000 lb.
Three Electrics	345 tons × 40 =	13,800 lb.
Total tractive effort		93,000 lb.

This is equal to 31,000 lb. for each electric locomotive.

On account of the very high frictional resistance of the Mallet engine as a towing load, this representative train is equivalent to 1980 tons, excluding the three electric locomotives, or a total of 2325 tons, on the 1.7 per cent grade. This is on the assumption that the draw-bar pull required for the Mallet is replaced by freight cars at 6 lb. to the ton; this represents the average freight train handled.

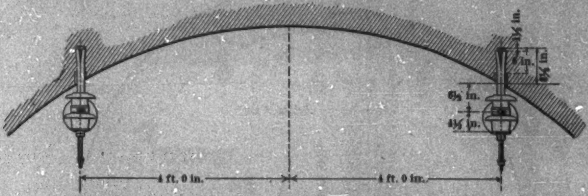


FIG. 22.—Cross-section showing trolley wires in tunnel

The tractive effort for the passenger trains varies from 40,000 to 50,000 lb., depending on the number of steam locomotives taken through; two electrics are ordinarily used, although one would answer in nearly all cases.

During this period there have been no delays due to failure of the electric locomotives, and but two trifling delays due to failures of the electric plant, both chargeable to the transmission line and both caused by accidents beyond the control of the operating force.

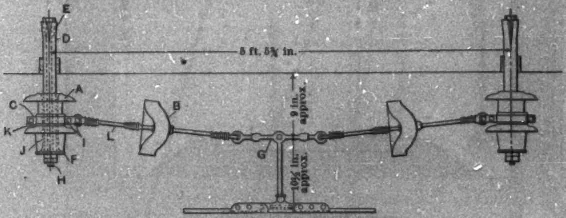


FIG. 23.—Longitudinal view of the tunnel suspension scheme—these supports are spaced 50 ft.

On August 11 the electric service was discontinued, owing to failure of both water wheels. Service was resumed on Sept. 9 and has been continued regularly since. The plant was taken over by the operating department of the railroad late in September.

The westbound service was not at first handled by the electrics regularly, as there is nothing in particular gained by braking the trains electrically on this short stretch, but now westbound passenger trains are so handled, for the benefit of the passengers.

Regenerating. A number of tests have been made to determine the power returned when regenerating; the following is typical:

TABLE V
TRAIN: MALLET ENGINE, 1550 TONS CAR WEIGHT, TWO ELECTRICS ON 1.7 PER CENT GRADE

Force due to grade	Frictional Resistance	Remainder for acceleration
Mallet.................... 8,500 lb.	11,500 lb.	– 3,000 lb.
1550 tons in cars.........52,500 "	9,300 "	+43,200 "
Three electrics...........11,700 "	2,070 "	9,630 "
Total for acceleration		49,830 "

This is equivalent to 1495 kw. delivered to the gears of the motors at 15 miles per hour.

The efficiency of the locomotive is approximately 80 per cent—hence the power returned to the line, should be 1200 kw. The test of this train gave 950 kw.; this difference is due to the standard practice, not yet abandoned, of keeping a certain number of car pressure retainers set on down grade.

The Mallet, instead of adding to the delivered power is an additional load that has to be carried by the train.

A similar test on a ten-car passenger train weighing 950 tons gave

Delivered power, calculated...........................	590 kw.
" " measured...........................	597 "

In this case there was no added resistance of pressure retainers.

These tests merely confirm the calculations, as they should. On a 1.7 per cent grade, then, one ton, descending at 15 miles per hr., will deliver 0.67 kw. to the system; on a 2.2 per cent grade it will deliver 0.91 kw.

Efficiency. The losses in the system when delivering 4000 kw. to the locomotive, at the west end of the Wellington yard are:

Place	Power Kilowatts	Per cent.
Power house low-tension bus-bars	4740	100
Substation " " "	4250	89.8
Trolley wheel of the locomotive	4000	84.5
Driving axles " " "	3320	70.

The average efficiency is somewhat higher than 70 per cent.

HANDLING OF TRAINS

The maximum duty was imposed upon this equipment from the outset. On account of very poor regulation of water wheels, steam has been used in one of the Mallet engines in starting the freight trains in the Wellington yard; an attempt has been made to use just sufficient steam to enable the Mallet engine to turn itself over. Steam is shut off at the portal of the tunnel; in addition to this, in order to provide smoother starting, a slight air pressure has been maintained on the locomotive at starting, which is gradually reduced.

On several occasions trains have broken in two, due to the trolley wheel on the rear locomotive leaving the wire and thus cutting off part or all of the power supply to the rear locomotives. This throws a greatly increased draw-bar pull on the front locomotive, and the consequence is that the train is jerked apart. This happened in the early stages of the work, and was due to the fact that the turn-outs were not in the best order, and also that the engineers had not sufficient experience in handling trains. Another means taken to avoid the broken draw-bars was to use the rear Mallet engine to assist the train over the trolley crossings in the Wellington yard; this was a temporary measure and has been discontinued.

Economy of Mallets. It is interesting to compare the performance of a Mallet compound locomotive under the same operating conditions as this system. The data for this are given by Mr. Emerson, superintendent of locomotive power of the Great Northern Railway Company, in a discussion before the American Society of Mechanical Engineers on locomotives of this type;* as an excellent performance he gives these data:

> Recent performance shows that on a round trip over this division the L-1 engines handled 1600 tons with a total of 43$\frac{5}{8}$ tons of coal, or equivalent to 25.13 lb. of coal per 100 ton-mile.

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* Transactions of the American Society of Mechanical Engineers Vol. 30, page 1031.

The division referred to is from Leavenworth to Everett, 108.7 miles. The work done per ton for a round trip over this run is readily calculated; from the profile I find,

Total rise, westbound	2212 ft.
" " eastbound	3440 "
	5652 ft.

and $5652 \times 2000 / 2.65 \times 10^6 = 4.26$ kw-hr., at the rail; this is the work done per ton in lifting the train; the work done against train resistance, assuming resistance to be 6 lb. to the ton, for 108.7 miles, is 1.3 kw-hr; the total work done in round trip per ton 5.56 kw-hr. There should be a negligible addition to this for starting the train.

The average train weight is:

Cars	1600 tons
One engine, 109 miles	
Second " 58 "	
Equivalent engine weight	380 "
Total	1980 tons

The coal used was 43⅚ tons, equal to 87,660 lb.

Coal per ton	44.3 lb.
Coal per killowatt-hour	8.0 lb.

A modern steam station can deliver one kilowatt-hour for 3 lb. of coal, at the bus-bar, which, with an efficiency of 70 per cent to the rail, gives a consumption of 4.28 lb. per kilowatt-hour at the rail; in other words, the Mallet compound requires nearly twice as much coal per kilowatt-hour at the rail as would be used in a modern steam station in the place of the hydroelectric station at Leavenworth.

ADVANTAGES OF THREE-PHASE SYSTEM

This plant has demonstrated, in my opinion, that the three-phase induction motor has certain very marked advantages over any other form of motor for heavy traction on mountain grades; these advantages may be stated somewhat approximately.

1. *Maximum electrical and mechanical simplicity.* This point is of great importance and was one of the principal reasons for using three-phase system; the motors will stand any amount of abuse and rough use.

2. *Greater continuous output within a given space than can be obtained from any other form of motor.* This, I believe, is

shown by comparison with other electric locomotives; it is due to the fact that the losses can be kept lower in a three-phase motor than in any other type. As Fig. 3 shows, the electrical efficiency of the motor is high for a wide range of load.

3. *Uniform torque.* This is important, particularly at starting. I believe that a three-phase motor will work to a three or four per cent greater coefficient of adhesion than a single-phase motor at 15 cycles.

4. *The possibility of using* 25 *cycles.* This is important, as it leads to a less cost and a better performance of power station apparatus; moreover, it is standard and the power supply can readily be used for other purposes, as well as for traction; a commercial supply can be provided.

5. *Constant speed.* This is ordinarily stated as a disadvantage of the three-phase motor; but in my opinion it is a distinct advantage in mountain service, particularly the limitation of the speed on down grades. It has also the advantage on up grades that meeting points can be arranged with greater definiteness. There is a general notion that the impossibility of making up lost time with the three-phase motor will be a decided drawback to its use. This would be true if there were the same liability to lose time with three-phase motors; but when a train can be counted on to make a definite speed, without regard to conditions of tracks or of its load, there is less liability to lose time. Although I am not prepared to state that a three-phase motor is suitable for cases where the profile is very variable, yet it is by no means certain that it would not work out well; the question is merely one of making a given schedule between two points with greatest regularity.

6. *Regeneration on down grades.* This matter has been discussed since the earliest days of electric traction, but, as far as I know, has not been, up to the present, put into practice. Although this result can be attained with other forms of motors, yet it is most perfectly attained by three-phase motors, there being no complications involved. This is of importance in reducing the power-house capacity required for a given service; although, no doubt, the saving in power-house capacity will not be as great as indicated by theory, owing to the various emergencies that must be provided for, nevertheless there will be a material saving. A 2500-ton train on the average down grade of 1.5 per cent will deliver about 1400 kw. to the system. The equivalent power house capacity would cost at least

$200,000; hence if only 20 per cent of this can be utilized the saving will equal the cost of one locomotive.

7. *Excessive short-circuit current is impossible* and consequently destructive torque on the gears and driving rigging is eliminated. There will be no necessity for the complication of a friction connection between the armature and driving wheels, as in the design of recent large direct-current electric locomotives.

8. *Impossibility of excessive speeds.* Even when the wheel slips the speed remains constant. Therefore, the maximum stresses put on the motor are less and are more accurately known than with any other form of motor.

DISADVANTAGES OF THREE-PHASE

On the other hand, the principal disadvantages of three-phase motor, for traction use, are commonly stated to be:

1. *The constant speed.* This is rather an advantage for this class of service.

2. *Constant power.* The fact that the motor is a constant-power motor and therefore requires the same power at starting and while accelerating as at full speed. While this is true, it is not a matter of any particular consequence in a service where the stops are very few, and consequently the proportion of total time spent in acceleration is small, and where the additional power required to accelerate the train is a small percentage of the power used by the train at full speed. In this particular case on the 2.2 per cent grade, when accelerating at the rate of 10 lb. to the ton, the power required during acceleration is only 20 per cent greater than that required at full speed; this is not a serious matter.

3. *Small mechanical clearance.* In this particular motor the clearance is ⅛ in., which is ample for all practical purposes.

4. *Inequality of load on several motors of a locomotive due to differences in diameter of driving wheels.* To meet this an adjustable resistance is included in the rotor of each motor, the motors are then balanced up and no further attention is required as long as the wear on the driving wheels is approximately the same. If, at any time, the load becomes badly unbalanced it is a simple matter to readjust the resistances.

5. *Low power-factor of the system.* This does not seem to be borne out by practice. The power-factor, as shown by the switchboard instruments in the power house, is 85 per cent. This is a good result and is much higher than the power-factor

of a well-known single-phase system that I recently had occasion to visit.

6. *Two overhead wires*. There is no doubt that two wires will cause more trouble than one, and in case of complicated yard structure it might not be practicable to use two overhead wires; but where the problem is that of a single track with an occasional turn-out or crossing there is, practically speaking, no more difficulty in maintaining two wires than one.

In brief, in service, of this character the three-phase motor has marked advantages in capacity, reliability, simplicity, and general trustworthiness, when compared with any other motor.

SOME MINOR ADVANTAGES OF ELECTRIC TRACTION

In the many discussions of electric traction which have recently taken place, I do not find several minor advantages sufficiently emphasized. One of these advantages lies in the fact that with electric traction the exact performance and condition of the locomotives and of all elements of the system is accurately known at each moment; on the other hand, with steam locomotives neither the engineer nor the motive power man can have any clear knowledge of the conditions of operation at the moment; he can only ascertain the performance of the locomotive by elaborate tests, which, as a matter of fact, are seldom made. The ratings and performance of steam locomotives are made up largely by " authority " based on a few tests from time to time, and take no cognizance of the actual condition of the locomotives. The importance of this, I think, is clearly brought out by the tests of the steam locomotive cited herein.

With electric locomotives the operation on a heavy grade becomes as simple as on the level; the engineers and train men feel much greater confidence in the electric locomotives and consequently the mountain division ceases to be a terror to them.

Electric traction will permit the use of very long tunnels, which are not now possible on account of difficulty of ventilation. There is no particular reasons why tunnels of ten or twelve miles should not be operated as easily as those of one mile.

The great increase possible in the speed of trains with electric traction and the consequent increase in the capacity of a single track will operate to postpone for a long time the necessity for double tracking. This double tracking on a mountain is a very expensive piece of business and this saving alone will, in some cases, more than offset the cost of electrical equipment.

A word in closing: the construction work in the tunnel and yards was carried out under great difficulties, owing to the necessity of not interfering with the regular service of the road. At times it was not possible to work in the tunnel for more than one hour a day, and for days at a time two or three hours was all that could be allowed, but in spite of this the work was carried out with very satisfactory speed, due particularly to the skill and ability of my assistants, R. Beeuwkes and W. S. Skinner, and the unstinted assistance of the engineering department of the road.

DISCUSSION ON "THE ELECTRIC SYSTEM OF THE GREAT NORTHERN RAILWAY COMPANY AT CASCADE TUNNEL."

NEW YORK, NOVEMBER 12, 1909

President Stillwell: We are to have the pleasure this evening of listening to the presentation of a paper by Cary T. Hutchinson on "The Electric System of the Great Northern Railway Company at Cascade Tunnel." It is certainly a fact of great interest that in this year, 1909, a three-phase railway installation of magnitude has been completed and put in commercial operation in the United States. Polyphase motors were brought to this country in 1888. Those which arrived in that year were rated about one-quarter horse power, but none of them, I think, ever succeeded in developing that output. At that time serious efforts were made by American engineers associated with one of our manufacturing companies to adapt this type of motor to railway purposes, but they reached the conclusion that the constant-speed characteristic of the motor rendered it unsuitable for such service. A number of years later DeKando, in Europe, undertook to adapt polyphase motors to traction purposes, and it is a pleasure to have an opportunity to record the admiration that I feel, that I think all American engineers feel, for DeKando's exceptionally able and original work in that development.

The three-phase system has been in use in Italy, and in Switzerland, for a number of years, and, since 1904, on what may be called a large scale on the Valtellina line. From 1890 until recently but little attention was paid in the United States to the practical application of the polyphase motor to railway purposes. It received during that period, it is true, careful study; but the conclusions reached were negative, so it was not introduced in commercial service in this country.

In the United States there are to-day three different systems operating electric traction of the heaviest kind; namely, the direct-current system, the single-phase alternating-, and the three-phase alternating-current systems. All of these systems, I think it may fairly be said, are doing their work not only successfully, but in a manner that shows a marked improvement over the steam locomotive operation that they have superseded.

The steam railroad managements of the country are beginning to awaken. They are asking which is the best system for general railway work, and that question must be answered by the electrical engineer. A member of the committee of the American Railway Association said to me this morning that he felt the art was not sufficiently advanced to justify his railroad in considering seriously the application of electric motors. Now, the fact is that we have a variety of methods, and it is important to accelerate the process that ultimately is to result in the survival of the fittest.

It is here, I think, that one of the functions of this

Institute comes in. In this country there is no government commission to decide general standard specifications and to pass on the claims of various systems before adoption, as is done, for example, in Germany. With us, the evolution of a system is not directed, except so far as commercial interests may influence it, or the consensus of opinion of the members of this Institute affects it. I am always glad, therefore, to have this subject presented, because there is nothing within the scope of the American Institute of Electrical Engineers that is of greater technical interest, or that compares with it in commercial importance.

Cary T. Hutchinson: I shall not attempt to cover the entire scope of the paper, but shall merely emphasize a few of the features of the work. The first is that this system was installed with the expectation that it will form part of a larger system, having a length of from 60 to 100 miles. At present it is merely a shuttle service through a tunnel from a yard on one side to a yard on the other, the distance being about 4.5 miles.

If nothing further than this were contemplated, it would seem that such electrification would constitute a very serious additional expense, and this doubtless would be true, although owing to the peculiar conditions under which the steam service has been handled there is an actual saving in operating expenses over this stretch of about $100 a day. The fundamental reason, however, was increase in capacity. This tunnel formed the congested point of the railroad system; under some conditions it was almost impossible to get the tonnage through the tunnel.

A short description of the method of handling the traffic under steam will indicate the difficulties that were encountered. Trains east-bound from the Pacific coast were from 1400 to 1500 tons trailing load with two Mallet compound engines. At the west end of the tunnel, at the foot of the grade, all trains were stopped, fires were hauled and cleaned, the engines took on a special high-grade coal, new fires were built and the engines remained in the yard for an hour or more, coking these fires in order to get rid of superfluous gas. In addition, a helper engine was kept in the yard, which used the same grade of coal and with the same precautions. The train was divided into two parts, the helper engine taking about 400 tons through and the two Mallet engines afterwards taking the remainder of the train, say 1000 tons.

When weather conditions were bad it was almost impossible to get trains through the tunnel; sometimes it was necessary to wait two or three hours after the passage of one train before it was safe to send a second train through. Frequently the steam pressure in the rear Mallet engine would fall from 200 lb. to 70 lb. or less, owing to the impossibility of maintaining fires on account of the exhausted condition of the air in the tunnel. The train would then have to stop and be split into two sections, and it would be necessary to back the rear engine out with part of the train.

These conditions also had a very bad effect on the train crews. Good engineers would not stay on the division; it was considered dangerous service.

Under these conditions Mr. James J. Hill, finally determined, after several years' consideration, to try out an equipment at the tunnel with the express intention of using it on the entire mountain division, if it proved to be satisfactory. These were the conditions that led to the adoption of this particular system.

W. S. Murray: As a single-phase man in other fields I wish to say that as far as the Cascade Tunnel *per se* is concerned, I am heartily in agreement with Dr. Hutchinson's chosen method of electrification. It is my belief that the physical conditions call for this method. Assume any piece of trackage, either one mile or 300 miles in length, at constant grade, whether zero or such a percentage that admits of adhesion of the locomotive driving wheels, and with no stops in the schedule (or if inclusive of stops then with exceedingly low train acceleration). Under these conditions, particularly where single track is involved, thus eliminating any complication of overhead construction, it is my belief that the three-phase system would be correctly applied.

Dr. Hutchinson says that traction developed by motors of the three-phase type admits of 3 per cent or 4 per cent greater adhesion than in the case where single-phase motors are used. Now, the single-phase motor is admittedly heavier than the three-phase motor of the same capacity, and, therefore, if it lack adhesion in its torque developing characteristic—which statement is by no means accepted by all—the deficiency is taken care of by its excess weight, thus illustrating the old adage, "It is an ill wind that bloweth no man good."

Though the subject treats of a three-phase installation, I am sure that Dr. Hutchinson will not object to an effort at drawing the line between the application of three-phase and single-phase apparatus. Dr. Hutchinson speaks of the advantage of a frequency of 25-cycles. This frequency is also applicable to single-phase installations, but it is true that the use of three-phase apparatus assures less costly generators. This saving, however, is offset in the case of single-phase installations by less costly switchboards. It is interesting to note that it is not much more expensive to use three-phase generators for single-phase distribution, as the new type of dampened field cuts down the rising voltage on the idle phase, making it possible to develop and use three-phase current for commercial requirements.

Concerning the speed of trains propelled by three-phase or single-phase motors. Infrequently it is said that a train under three-phase propulsion is more certain of making its schedule, on account of its constant-speed characteristics. Now, there is no desire on the part of the single-phase motor not to go. If we should place impress 500 volts on the terminals of one of Dr. Hutchinson's three-phase motors, and on one of the New

Haven locomotive single-phase motors, subjecting neither to any load, the former, if a frequency of 25-cycles were used, would arrive at 300 revolutions and go no higher, while the single-phase motor would, in a very short interval of time, arrive at a speed far in excess of that of the three-phase motor. The speed of the single-phase motor depends simply on the balancing resistance of the train, at the voltage applied to the motor. If the required balancing speed is 60 miles an hour, there is a voltage that corresponds to this on the transformer; it is simply for the engineer to see that the controller is on the right notch to supply it. Speed is a direct function of voltage, and the single-phase motor receives its voltage without the interception of resistance. Resistance, both within and without the circuits of the motor, means loss. In the case of the three-phase motor, except cascade connection, resistance has to be inserted for all speeds below the normal slip-speed of the motor.

The true speed-torque traction curves for railway motors were given by the direct-current series motor long before the alternating-current motor, either of the induction or the single-phase type, put in an appearance. In general it may be said that this type of motor conserves the apparent necessity of a service having a motive power which, at high efficiency, will take care of variable-speed requirements made necessary by accelerations, slow-downs, and stops. Horse power is directly proportional to speed and torque. On a grade the series motor admits of a lower speed, which, taken with the increased torque requirements, tends to keep the horse power constant; in the case of the polyphase motor, the speed remaining constant with the increase of torque required, due to grade, the horse power rises. It is thus clear that the single-phase motor, with speed characteristics similar to those of the direct-current series motor, admits of maintaining nearly constant load upon it under varying conditions of grade: with the three-phase motor, the load, for the reasons stated, must vary over exceedingly wide limits. For example, Dr. Hutchinson's locomotive, when hauling a train up a 2.2 per cent grade, has to develop six or seven times as much power as when hauling the same train on a level. A constant load-factor cannot fail its appreciation, be it in a power house or an electric locomotive, and the illustration previously made is an attempt to bring out the just reason for Dr. Hutchinson's application of the three-phase motor to special conditions of constant grade, no stops or low acceleration, and that of the single-phase motor in the field which admits of great variation in grades and higher acceleration.

To exemplify more concretely the point made in the previous paragraph, Dr. Hutchinson says that the Cascade Tunnel electric locomotive requires only 20 per cent more power in accelerating a train in the tunnel grade than in running the same train on the same grade at full speed. This is interesting, and convincing as to the ability of an electric locomotive of this design to take care of the concrete conditions cited.

It is also interesting to analyze this conclusion. To accelerate a train on grade it is necessary to overcome three classes of resisting forces:

1. The inertia of mass.
2. The resistance of frictional parts.
3. The resistance of gravity.

At an acceleration at the rate of 0.1 of a mile per hour per second, the resisting force due to inertia of mass is 10 lb. per ton. The friction per ton in a freight train, inclusive of the locomotive, may be estimated at 8 lb. per ton, though this is high. The grade is stated to be 2.2 per cent. Gravity offers, therefore, at 20 lb. per ton, a total of 44 lb. Thus, the total resistance per ton to accelerating on the grade in question is 62 lb. After the train has been accelerated to speed, 10 lb. of this 62 lb. drops out, due to the disappearance of mass inertia. The ratio of 62 to 52 is practically 20 per cent, as Dr. Hutchinson points out. Under this analysis it is not difficult to see, however, why the ratio is so small. If we drop the acceleration to 0.05 of a mile per hour per second, then the difference would have been only 10 per cent. The two things that cause this ratio to be so small is the low acceleration and the high grade.

Exactly opposite conditions exist in high-speed suburban passenger service, where the acceleration is exceedingly high and grade is practically eliminated. As an example, under the conditions of no grade, a passenger train being accelerated at 0.7 of a mile per hour per second will require 70 lb. to the ton, and assuming the average friction per ton up to 60 miles an hour to be 10 lb., the total pounds per ton required is 80. After the train has arrived at the balancing speed of 60 miles per hour, mass inertia disappears; the remaining resistance, train friction, may be 15 lb. per ton. Now, it is seen that the ratio of the torque required to accelerate this train to the torque required to keep it at 60 miles an hour is 80 to 15, or the increase instead of being 20 per cent is 533 per cent. An acceleration of 0.7 mile per hour per second is not unduly high for a suburban service on trunk lines, and this analysis is an attempt to bring out the great difference between the case cited and the duty requirements of the Cascade Tunnel locomotives.

I agree with Dr. Hutchinson that in regard to mechanical clearance, ¼ in. is ample for all practical purposes. The method suggested for dividing up the load uniformly on the motors by the insertion of resistance would seem to be practical. As these resistances must be continually in series it would be interesting to know what percentage of loss is incurred; doubtless it is low.

The single-phase system, such as, for example, that of the New York, New Haven & Hartford Railroad Company cannot claim any higher power-factor than that mentioned by Dr. Hutchinson in the case of the Cascade electrification. Power-factor in a system is an interesting detail. It is possible to be misleading. The New Haven road is a large user of single-phase power, and its power-factor seldom rises above 85 per cent. Indeed, it is more frequently below 80 per cent. It is well to know, however, exactly what power-factor stands for. A high-voltage system primarily stands for very low transmission losses. Let us assume, for example, that the actual transmission losses of the New Haven systems are between 5 and 10 per cent at unity power-factor. Even should the power-factor sink as low as 75 per cent, this would mean that the line loss, instead of being from 5 to 10 per cent, would be from 6.7 to 13.3 per cent. Remembering that many systems have a normal loss of 25 per cent, it would seem that the fluctuation of power-factor, even within wide limits, is not serious.

I am in agreement with Dr. Hutchinson that the yard proposition on two overhead wires is not practicable, and I also believe that this is true of main-line tracks where high speeds and many switches are involved. I wish to support Dr. Hutchinson's views in regard to simplicity, capacity, and reliability of the induction motor. I have always had the greatest respect for this kind of motor. It is my great regret that its electrical characteristics do not, in my belief, conform to those required by the general traction problem. It is to the alternating-current series motor what the direct-current shunt motor is to the direct-current series motor. The direct-current shunt motor has disappeared forever on all traction lines, and I do not believe that it can reappear under the cloak of alternating current.

E. B. Katte: Sometime ago I had the privilege of seeing one of the electric locomotives in the works of the manufacturing company and believe it will be hard to improve upon either the electrical or mechanical design for the speeds for which the engines are intended.

The reasons for adopting a three-phase system over the whole mountain division are quite obvious, but I am surprised to note that this same system would probably have been used if only a four-mile tunnel section was to have been considered. Without going into figures, it would seem that a direct-current system with storage batteries would have made unnecessary the use of steam locomotives in starting electric trains, and at the same time would have relieved the power station from the sudden inrush of current, thus securing better regulation at the water wheels. And further, by adopting multiple-unit control for the locomotives, two or more at the head end of a train could have been operated with one-half the number of men.

Dr. Hutchinson describes the ground-wire, provision for which has been made on the top of the transmission-line poles, but states that it has not yet been installed. I wish he would explain why the ground-wire was finally omitted. When the transmission line of the New York Central was designed, similar provision was made for a ground-wire, but after further consideration it was left out; for the reason that the poles were of steel and each carefully grounded to a large copper place set in permanently wet ground, and it was believed that each pole would act as a lightning rod and thus protect the line. However, on the Great Northern line the poles are wooden and the insulator pins do not seem to have been grounded, consequently if a ground-wire is ever necessary, these would appear to be conditions under which it would be most valuable.

The fact that wooden poles are used through forests leads me to ask if any special protection against destruction by fire was adopted. Last year when estimates were made for the information of the "up-state" Public Service Commission, covering the cost of electrifying railroads through the state forest lands, it was considered necessary to use steel poles because of the danger due to forest fires.

The experience with insulators covered with soot from steam locomotives is similar to that on the New York Central system. At first we were much perturbed because of the soot which was accumulated upon the 11,000-volt insulators in yards used by steam locomotives through which the transmission line passed, but after careful tests on several insulators which were well covered with soot it was found that the flashing-over point was several times the normal voltage even when the soot was well saturated with water.

Among the minor advantages to be derived from electric traction, brought out in this paper, is the possibility of knowing at any instant, by the direct reading of meters, the exact operating condition of any element of the system. I believe this to be more than a minor advantage and think it of very great importance and help to those charged with the safe and reliable operation of trains.

Bion J. Arnold. During the last summer I rode through the Cascade tunnel several times on the electric locomotives described by Dr. Hutchinson. I was interested in the operation of the system. It seemed to perform its work as satisfactorily as any direct-current or single-phase installation I have ever seen. It had the objectionable double overhead conductor, and the yard was necessarily somewhat complicated on that account. I agree with Mr. Murray that for a railroad with many yards—and many yards are the rule with steam railroads if an overhead conductor is to be used—the single-phase installation is preferable. That is one of the principal reasons why the single-phase system was used for the tunnel of the Grand Trunk Railway system between Detroit, Michigan, and Sarnia, Ontario—a tunnel installation similar to this, terminating at each end in a vast yard with a number of tracks, and located in a climate where snow and ice were likely to cover tracks—over which the train movements were infrequent. I concluded that under such conditions a third-rail might become iced or covered with snow, making it difficult at times to move trains. These and other conditions impelled me to adopt the single-phase system, and at a time when such a system had not been tried on heavy traction work. The Grand Trunk installation has been in successful operation for some years, and so far as I know there is no desire to adopt any other system.

We all know that both the direct-current system on the New York Central and the single-phase system on the New York, New Haven and Hartford are operating successfully. Mr. Sprague and others are advocating a high-potential, direct-current system, and I have no doubt that within moderate limits that system will be equally successful. All of this tends to show that while we may individually believe in some particular system, none of us can prove conclusively that his is the ideal system—and that when conditions arise which call for the development of a new system, such a system will be properly developed and applied.

I am surprised at the excessive friction of the Mallet compound locomotives. Dr. Hutchinson gives it as an average of 46 lb. per ton. Ordinarily the friction load for steam railway trains is estimated at 6 lb. per ton on level straight track. This excessive friction is probably due to the greater number of cylinders, reciprocating parts, and extra weight of the valve motion of these engines; and it indicates that some of the advantages of these immense engines are offset largely by this excessive friction, especially when they become a trailing load. What is the friction of these engines when running under steam? I assume that this table gives the friction when the engines are being pulled as trailers by the electric locomotive.

Dr. Hutchinson says he adopted a method which gave him a single speed, for his electric locomotives and that resistance was used when starting. He also says that one of the reasons for doing this was to obtain simplicity, giving as an additional reason that the power cost was nothing, being developed by water power, consequently he could afford to waste it in starting the locomotives. But such practice would not do in case the power were produced by a steam power plant on a railroad of any great magnitude. I think, therefore, that a different conclusion would have to be drawn as to the method of control to be adopted, in case the three-phase system were made applicable to a large railway system. In this respect Mr. Murray has pointed out the superiority of the single-phase system, as far as economy of operation and securing of variable speed is concerned.

F. N. Waterman: As one who has advocated the consideration of three-phase motors for railway work, I am particularly gratified by the evidence of its advantageous application as set forth in the paper of the evening. There is one interesting property of induction motors which is not exhibited in the present instance, because only one train is operated; namely, the action of moving trains as fly-wheels to keep down the peaks or to minimize the fluctuations of output of the central station. This was illustrated by the operation of one of the electrified divisions of the Italian state railways, known as the Valtellina line. The traffic comprised freight and passenger service, with an average of from four to six trains running simultaneously. With only one train running, as occurred at the extremes of the day, the ratio of maximum to average ordinate of the output curve was about 3.5 to 1. The average run was short, requiring frequent acceleration. With a number of trains on the line, the ratio of maximum to average output fell to 1.7 or 1.8 to 1, giving a load-factor of 55 to 60 per cent. The reason why the ratio of maximum to average was as favorable as 3.5 to 1 with single train operation, was the employment of the cascade control for most of the trains. The freight was handled at that time, in the manner adopted by Dr. Hutchinson, by rheostatic control with a low rate of acceleration. The remarkably favorable results on the Italian state railways was unquestionably due to the peculiarity of induction motors, that they cease taking current if the frequency falls by the amount of their slip, and return current if it falls to a greater extent. The water wheels driving these generators fell off in speed some five per cent, as full load came on, while the average slip of synchronously running trains was less than one per cent. Hence, as the shock of starting a train came upon the power house, the frequency fell, and it had to fall only one per cent entirely to relieve the station of other loads. A further fall would cause the moving trains to return energy to the line and help supply the starting current. This momentary relief of the station resulted in the high load-factor noted. It would appear that this property of induction motors should be of great value where a small number of trains is operated.

Of course, relief of the power house by this means is only momentary. Whether it would be of consequence at all in such a proposition as Dr. Hutchinson is dealing with is perhaps problematical. The starting of a 1600-ton freight train is a very different matter from the acceleration of a 125- or 150-ton passenger train, and the time-interval during which the fly-wheel action is effective might very readily be so small that the advantage would not be realized to anything like the same extent, but it is a property resulting from the constant speed characteristic of the motor, which in many cases is of large consequence, and in any case is extremely interesting, as being not merely a theoretical deduction, but as proved out in the practice of the Italian State Railways. The tandem control, which has been spoken of as " messy ", is employed by the Italian state railway, even on a recent installation, which is like this Cascade installation in being a through haul on a constant grade.

I had some calculations made a short time ago showing the effects of tandem control of three-phase motors in comparison with the series-parallel control of the New York Central locomotives. It was impossible to include a computation for the single-phase locomotive, because sufficiently accurate information regarding the performance of single-phase locomotives was not available. Table I shows that the tandem control with two speeds—a method that leaves the entire equipment available for either kind of running—is at least not inferior to the New York Central locomotives, employing four motors and their three groupings, in respect of maximum draught on power house or total energy consumption, but is rather better. If handled on the basis of constant-current input, which is not the custom in direct-current practice in this country, I believe the three-phase locomotive will show rather a noticeable advantage when the application of the three-phase motor to railroad work has received the same thorough study and development as given to the direct current motor. If experience abroad may be taken as a criterion it will be found superior for many purposes, to any other form of motor.

COMPARISON OF THREE-PHASE AND DIRECT CURRENT LOCOMOTIVES.

Type of locomotive	Total train weight tons	Net train weight tons	Distance in feet	Time in sec.	Speed maximum miles per hour	Kilowatt maximum	Kilowatt hours	Watt-hours per ton-mile	
								gross	useful
New York Central (weight 95 tons)..	435	340	27300	426	58.4	1920	110	49.4	62.8
Valtellina 2 speed type (weight 68 tons)	408	340	27300	426	58.5	1660	104	49.1	59.4
Valtellina 3 speed type (weight 68 tons)	408	340	27300	425	58.5	1660	91.5	43.5	52.3
New York Central..	265	170	29800	403	60.5	1800	82	54.9	85.5
Valtellina two-speed type............	238	170	29800	404	59.5	1660	71	52.8	74
Valtellina three speed type............	238	170	29800	402	59.5	1660	60	44.7	62.5

Notwithstanding the use of cascade control on the Valtellina locomotives, the control apparatus is much more free from complicated or messy apparatus than that of any electric locomotive in use here. This results from the use of liquid rheostats with compressed-air control. A limit relay is used to maintain the rotor current constant, and the rate of acceleration is determined merely by the notch in which the handle of the controller is set. In the simplicity and small space requirements of the control apparatus there is a great contrast in the appearance of these Valtellina three-phase locomotives and that of the large locomotives in use in this country.

From a mechanical point of view I was much interested in the motors of the Italian state railways. The clearance used there between rotor and stator is 2 mm., about

$\frac{1}{12}$ in., and the wear of the bearings, in some 60,000 miles of operation on these locomotive motors, was about 0.3 mm. The reason for such a result is that the collector rings are outside the bearings, leaving it only necessary properly to proportion the spiders to have virtually the entire interior of the rotor for bearings and lubricating means. While the three-phase motor, particularly if arranged for cascade operation, requires an air-gap as small as $\frac{1}{12}$ in. the remedy is present in ample bearing space. Dr. Hutchinson points out some of the advantages of the three-phase motor; the foregoing seem to me to be further advantages.

J. H. Davis: The system described marks an epoch in the history of heavy railroad electrification in the United States. It is the first attempt in this country to use the three-phase induction motor for handling heavy passenger and freight trains on a trunk line railroad.

I am especially impressed with the importance of the electrical engineer's decision in recommending the adoption of a certain system of electrification. His decision is second in importance only to that of the engineer locating the railroad. A decision to use this or that system of electrification for a certain purpose, as, for instance, handling heavy traffic over a mountain division, will, of necessity, have great weight in determining the system of electrification to be used when other divisions of the road are electrified. The system thus adopted may or may not be that which is best suited for the desired extension. If the entire road is eventually electrified, one system of electrification should be used throughout, although this system may not be best adapted to all of the various conditions to be met. Therefore the system adopted should be that which is best adapted to the requirements of the road as a whole. The necessity for interchange of equipment from one division to another is well known, and in meeting this requirement the electrical engineer can best obtain simplicity of equipment by confining himself to one system of electrification. The gain in this direction will be more than sufficient to offset the loss due to the adopted system not meeting in the best way some of the conditions.

Inasmuch as the conditions at Cascade Tunnel are very similar to those encountered on the Belt Line Railroad of the Baltimore & Ohio, where direct-current electric traction has been used for 14 years—this being the first installation of electric locomotives for heavy traction purposes in the United States—a comparison of the physical conditions, train weights, tonnage handled, equipment used, etc., may be of interest. This comparison I give in the subjoined Table I.

It might be added that the working conductor on the electrified section of the Baltimore & Ohio was originally placed overhead, its design, however, being very different from that used at the Cascade tunnel. The low working voltage on the Baltimore & Ohio necessitated the collection of a large amount of current, and a rather complicated overhead construction was necessary. Serious trouble was experienced in maintaining this overhead structure, and for this reason it was abandoned and the third-rail installed.

TABLE I.

Physical conditions:	B. & O. R.R.	G. N. Ry.
Length of electrified section	3.7 miles	4.0 miles
Ruling grade	1.5%	2.2%
Average grade	1.0%	1.7%
Length of longest tunnel	7,400 ft.	13,873 ft.
Train weights:		
Freight, including steam and electric locomotives	1928	2075
Passenger " " " " "	990	906

Tonnage handled per day:	B. & O. R.R.		G. N. Railway	
	No. of train	weight	No. of train	weight
Passenger	21	6,630	3	2,690
Freight	28	29,600	2.5	5,290
Special	0		1	470
Totals	49	36,230	6½	8,350

Equipment:	B. & O. R.R.		G. N. Ry.
	Pass.	Freight	Freight
Number of locomotives	5	2.5	4
Weight, tons	90	160 (2 units)	115
Number of motors	4	8	4
Rated horse power	1,100	1,600	1,900
Tractive effect, rated load	26,000	70,000	47,600
Speed at rated load, miles per hour	16	8.5	15

NOTE:—Data on B. & O. equipment based on natural ventilation: Great Northern on forced ventilation.

L. R. Pomeroy: About seven years ago I made an examination of the Cascade Tunnel to determine the possibilities of electrification. At that time it was very difficult to arrive at the actual cost of steam operation, on account of the fact that the motive power statistics furnished were for average and general conditions, complicated by the addition of constructive switching and arbitrary mileage.

Since then I have been furnished with a road test of a Mallet locomotive over the section described in the paper, namely from Leavenworth to the Cascade Tunnel summit, a distance of 32.4 miles, with an average grade of 1.35 per cent and a limiting grade of 2.2 per cent. Also from a neighboring road, having similar physical conditions, an actual coal record; that is, tons of coal used for a period of six months, of individual classes of locomotives, representing 156 locomotives making 1,382,092 miles, and consuming 174,121 tons of coal, as follows:

No.	Class	Engine-miles	Tons of coal	Pounds per 1000 ton-miles	Pounds per engine-mile
55	2-8-2 simple.	291,070	33,418	191	230
6	2-8-2 compound.	81,150	10,275	175	251
24	2-8-0 simple.	299,036	33,931	345	227
71	2-8-0 compound.	710,836	96,479	306	271
156		1,382,092	174,121		

Some figures of the test referred to are as follows:

Distance	32.4	miles.
Running time	4 hr. 0	min.
Time lost in stops	3 " 4	"
Total time	7 " 4	"
Average speed (miles per hour)	8.1	miles.
Pounds of coal used per trip	23,100	lb.
" " " " " square foot of grate, per hour	74.03	"
" " " " " mile	717	"
" " " " " 1000 ton-miles	896	"
Average tonnage hauled	810	
Average number of cars per train (all loaded)	21	
Average grade	1.35%	
Maximum or ruling grade	2.2 %	
Indicated tractive force	60,000	lb.
Type of locomotive 2-6-6-2 (L2)	Mallet	
Total weight of locomotive	225	tons.

From the foregoing data the writer desires to present a few deductions.

A train with a trailing load of 2500 tons over the section of road on which the test was made will require about 5750 kw-hr. at the rail per trip.

Assuming a modern steam generating station, the coal used per trip at 15 miles per hour would be about 5 lb. per kw-hr. (at the rail) or a total of 28,750 lb. With the same tonnage per train under steam conditions at 15 miles per hour, three steam locomotives would be necessary.

Increasing the speed of the steam train from 8.1 miles per hr. to 15 miles per hr., reduces the tonnage about 30 per cent per locomotive. 810 tons trailing load plus 225 tons, the weight of the locomotive, times 70 per cent, equals 725 tons per locomotive. The coal consumption of the steam train then becomes 32 miles times 717 lb. per mile times three locomotives, equals 68,832 lb. Percentage of difference in favor of electricity:

$$1-\frac{28{,}750}{68\ 832}=58 \text{ per cent.}$$

Going back to the coal used by the 156 steam locomotives—these locomotives are used on two mountain divisions—for six months; namely, 174,121 tons. For a year the amount would equal 348,242 tons. At the rate of $2.00 per ton for Crow's Nest coal, the cost of coal equals $696,484. Also the cost for water used would be about $25,000. It has been shown that the coal saving amounts to 58 per cent. Calling this one half or 50 per cent, the saving would equal $348,242. It is claimed that the Mallet type of locomotive is 30 per cent better than the types composing the 156 locomotives referred to. We will, therefore, reduce this amount to correspond. $348,242 times 70 per cent equals $243,769; add the saving in water, $25,000, and the net saving then becomes $268,769. This amount capitalized at 5 per cent represents $5,375,380. This amount alone, not figuring on other savings, such as train crews, reduction in train-mileage with the same tonnage, and the advantage of a great increase in capacity, would go to show that such a mountain section comes very near being a situation where we can accomplish by electrification what is now impossible under steam conditions.

In the table of test data it will be seen that the time to make the run was 7 hr. and 4 min.; time consumed in stops or laying in side tracks, 3 hr. and 4 min.; time in motion, performing useful work, 4 hr.

Approximate figures from four railroads which give separately in the annual reports the coal per locomotive-mile for freight and passenger service, based on the total coal charged to engines for the year, the consumption per horse-power-hour is as follows:

	Passenger	Passenger and Freight	Freight
Road A	12.30		9.64
" B	12.86		11.20
" C	14.00		10.00
" D		10.63	

while from individual road tests we find the coal consumption frequently is from 4 to 8 lb. per horse-power-hour.

The point that I desire to make is that it is not quite fair to the electric side to base the comparative costs on a road test without adding a liberal amount to cover this "contingent" feature.

In Tables III and IV the resistance of the Mallet locomotives is shown to be in the neighborhood of 50 lb. per ton exclusive of the resistance due to gravity. This is not to be wondered at when the sizes of the pistons are taken into consideration. The L-1 locomotive has cylinders 21.5 in. and 33 in. by 32 in. stroke and the combined area of the four pistons is 2436 sq. in. If atmospheric pressure of 15 lb. per square inch is figured against the low-pressure pistons only, the thrust equals 25,659 lb. A large share of this piston resistance is by-passed, but the fact that these locomotives cannot drift freely down a hill without a slight opening of the throttle, and from the tests shown in the paper, it would seem that the by-pass valves should be supplemented by some form of drifting valve which would result in materially reducing the resistance found in towing the locomotive with closed throttle. It is customary with some railroads to base the value of saving due to elimination of curves and grade reduction, not on the increased capacity, but on the money value of a reduction in train-miles. For example, on a division of 225 miles having seven freight trains per day the value of each one per cent in reduction of train-miles is about $3000 per annum, the capitalized value of this amount at 5 per cent per annum equals $60,000 for each one per cent of saving. The rate per train-mile being 50 cents, which represents the costs directly affected; that is, transportation expense not general expenses. This being the case, figures representing costs of electric service on this basis will directly appeal to railroad managers; whereas figures based on increased capacity are more or less problematical and open to doubt.

W. N. Smith: Although for a dozen years or more the three-phase system has been firmly established as the standard for general power transmission, certain disadvantages incident to its use have until now deterred engineers in this country from undertaking to avail themselves of some of its inherent advantages in heavy electric traction. It has been reserved for the author of the paper to be the first in the United States to reduce theory to practice and to place before us a general description of the construction and performance of a type of electric locomotive which, so far as this country is concerned, has never before emerged from text books and technical papers.

It seems to me that in the case here treated, operating conditions are such that the advantages of the three-phase system are of maximum importance, and the disadvantages of minimum importance. The relative advantages are clearly stated by the author and need no further comment. On the other hand, the chief disadvantages of the three-phase system, reduced to their lowest terms, are the harnessing of the inherently constant-speed motor to variable-speed duty, and the necessity of two trolley wires instead of one.

The first objection is largely minimized in this electrification by the nature of the train service and the character of the railroad line itself, both of which favor maintaining a constant speed. Whether or not there is any valid objection to maintaining a constant speed on a long railway line on the surface, there can certainly be none to doing so in a tunnel; and the speed is so moderate that the relatively inefficient performance during acceleration is not of long duration in proportion to the entire length of the run. In this case the acceleration seems to last about 1.5 min. out of the 12 to 14 min. that would be required to make the tunnel run.

The objection to two trolley wires is partly obviated in this case by the slow speed of 15 miles per hr. In my opinion this is the salvation of the wheel-trolley contact system here adopted. But even slow speed cannot mitigate all the disadvantages of two trolley wires of opposite polarity.

I have somehow received the impression that our European friends operate their railroads under some conditions that seem inapplicable to our roads. They appear to have a somewhat different view-point, to which both the employes and the public are accustomed: they pay strict attention to methodical detail all down the line, and subordinate the results thereto; while in this country the aim is more toward the final result and all possible time-consuming details are regarded as secondary to that result. This is the only way I can account for the favor with which the Europeans apparently regard the use of two trolley wires. They seem to have tackled this phase of the problem with remarkable freedom from the prejudice against it that has always existed in this country.

In a long straight tunnel taken by itself the double-trolley construction adopted by the author does not seem to present any unusual difficulties in maintenance. It seems to have been experienced in long-tunnel electrifications that the transition period from steam to electric power is the time when insulation is most likely to fail. The worst difficulty with the double-trolley wire seems to me to be at track intersections where moving contact must be made at will, upon intersecting wires of opposite polarity, without risk of short-circuit, and without danger of temporarily checking headway and injuring draft-gear by losing power for a few seconds when accelerating a heavy train at slow speed. The first of these considerations is all-important. The second depends on how many chances it is safe to take by temporarily cutting off or reducing the locomotive torque while starting a heavy train. Under the conditions of the Cascade Tunnel electrification, with main and side tracks at tunnel portals on a two per cent grade, it would seem necessary to have two sets of trolleys in contact, one set at each end of the locomotive when passing switches, at least whenever conditions make steady acceleration difficult, as with snow on the rails and journals stiffened by frost, and excessive train weight.

The paper betrays some dissatisfaction on the part of the author as to results so far accomplished with the double-trolley system as here developed. In working out improvements he will have the sympathy and encouragement of all who realize that, after all, the mechanical reliability of the moving contact system is the very foundation of successful electric railway operation, regardless of the kind of current employed. It is this feature that appeals to me as being susceptible of the greatest improvement. It is in respect to the trolley problem that the single-phase system is likely to be regarded as superior for some time to come.

It seems to me that future development in the perfection of the moving contact will be in the way of the wide roller type with pantagraph mounting, as distinct from the narrow trolley wheel or the sliding shoe; for the sliding shoe, widely used for high-speed work at the present time, seems susceptible of further betterments, if wear and tear at high speeds and heavy currents are to be overcome.

It is quite conceivable that ultimate speeds of 20 to 30 miles per hour may sometimes be thought advisable for some classes of train service on a mountain-grade line of this type instead of the 15-mile speed chosen for the heavy freight service of this installation. This refers more particularly to fast passenger and light freight trains. Train-speeds that operating economy may demand in the future ought not to be rendered impossible by the limited reliability of the time honored trolley wheel for high speed in such heavy service, particularly when passing switches.

The same considerations of speed prompt the opinion that the next locomotives to be built for this electrified section, or a similar one, will be fitted either with pony wheels or with side-rods for coupling to motors placed on top of the frames, or possibly with both of these contrivances. There seems to be no mistaking the tendency that has set in during the last two or three years, for electric locomotive construction to be guided more and more by the experience gathered during the two generations of steam locomotive practice. The boasted simplicity of the geared or gearless motor hung directly on the locomotive axle has proved disadvantageous in some other respects. The increased flexibility of locomotive design from the mechanical standpoint, which is consequent upon placing the motor on top of the frame and using side-rods and jack-shafts, and the general mechanical uniformity with the frames and running gear of existing steam locomotives, will make an electric locomotive appear more like a standard piece of machinery to the railroad operating man than has hitherto been the case. The great advantages will be the raising of the center of gravity, the ready standardizing of mechanical parts independently of electrical equipment, and the ability to use the same arrangement of frames and running gear for either direct-current, single-phase, or three-phase motors. With such construction safe speeds are not limited to 15 miles per hour. Without it, track maintenance and liability to derailment would likely continue to be as disadvantageous to the electric locomotive at high speeds as they have in the past.

One feature of the author's description of the performance and rating of the locomotive motors which is of particular interest is that emphasis is put upon the continuous capacity, as well as the one-hour rating and the maximum tractive effort. In spite of the objections that have been urged against the term "continuous capacity" as applied to railway motor specifications, the author apparently takes it for granted that it is bound to survive; and it is to be hoped that its evident applicability to the specification of locomotive motors will lead to a more universal recognition of its appropriateness in specifying the smaller sizes of railway motors.

The author's estimate of the power station fuel consumption of these electric locomotives as compared with the Mallet compound steam locomotives, while interesting, would be more convincing from an economic standpoint if submitted in greater detail. The chief advantage of electric traction, demonstrated by the paper, is the increase of the capacity of the tunnel and adjacent mountain section, by doubling the speed possible with steam locomotives of the most economical type. Moreover, there are still other operating features, such as the location of passing sidings, and the signalling and train-dispatching system governing the physical possibilities of getting the trains past each other at the increased speed, which have need of full consideration in order to determine the economic value of the increased speed made possible by the electric system.

F. S. Denneen: The chief reason for selecting the direct-suspension type instead of the more elaborate catenary type, now so popular, was the greater mechanical and electrical simplicity of the former. It is at once evident that with two wires over each track, with 6600 volts between them and between either wire and the ground, the problem of insulating the catenary type of construction would be a difficult one. With several tracks having numerous switches and intersections the problem would be greatly complicated. Within the tunnel the available head-room and side-wall clearance were so small that the catenary suspension was not desirable. With the speed limited to 15 miles per hour, many of the advantages of catenary construction over the direct-suspension type would be lost. A careful study of the entire situation then led to the conclusion that the direct-suspension type would fully meet all operating requirements, and, at the same time, because of greater simplicity, repairs could be much more quickly made, thereby reducing the danger of appreciable delays in the service.

The overhead structure in the yards on single track consists of the bracket shown in Fig. 20. It will be seen that each phase is supported by an independent span, and that auxiliary insulation is provided in every case; that is, the major insulation may be said to consist of the two heavy porcelain strain insulators marked *E* and the auxiliary insulation, the wood break strains marked *A*. The porcelain strains are rated for 10,000 volts, while the wood break strains might be rated at 3300 volts, or more. If I remember rightly in certain parts of the yards it was necessary to provide overhead construction for as many as six tracks; the details of the design work have somewhat slipped away from me, because it is more than a year and a half since I had anything to do with it. It was not possible to place any supporting means between the tracks and the entire overhead structure had to be carried on cross-span construction, which, because of its flexibility, made the insulation a difficult matter.

Fig. 17 shows that wires of the same phase are carried upon one cross-catenary, while those of the opposite phase are carried upon another one, also that there is insulation between the wires of the same phase over different tracks. This was done in order to make the tracks entirely independent, and to make it possible to cut out any one track or any set of tracks. Fig. 18 shows a unit system, that is, it is arranged so that by removing one or two bolts a new piece or a new unit can be quickly inserted without serious interruption to service. Adjustment by means of suitable turn-buckles is provided at every point where necessary.

Within the tunnel, the end-section of which appears as Fig. 21, the details of the overhead construction appearing as Fig. 22 and 23, bronze fittings were used in most cases. There was a great deal of moisture and drip, but it was not known how much of the moisture was due to the steam from the locomotives and how much from the drip through the tunnel roof. To provide against corrosion, bronze was largely used. Dr. Hutchinson says it is possible that malleable iron and steel properly galvanized would have done as well.

Dr. Hutchinson refers to the trouble experienced at the intersection of lines due to the trolley leaving the wire, this trouble occurring as the trolley wheel crossed the pan-casting. At the time the layout was originally made, a scheme was considered for automatically turning the tongue portion in the pan so as to carry the wheel across in the proper direction, but this scheme complicated the arrangement and was not used.

When the original tunnel layout was made, the trolley wires were set 5 ft. apart, but after the designs had been worked out and approved by the railway engineers, the officials of the road decided that they wanted the entire central part of the tunnel clear, so it was necessary to set the trolley wires out to a separation of 8 ft. within the tunnel, which added a number of difficulties. The clearance between the side walls and the trolley on either side was only approximately 14 in., and as it was necessary to prevent the trolley from swinging, it was somewhat difficult to put in steady members with double insulation. The steady device used consists of two porcelain insulators of the ordinary skirt type of about 22,000 volts rated capacity, placed in series; the insulators are fastened together in a vertical position by means of a U-shaped casting with the ends cemented into the insulator pin holes. Each insulator carries a malleable iron cap, one of which is attached to the trolley wire and the other to the side wall of the tunnel. The connecting U casting is provided with a flanged portion all round, to protect the porcelain from blows from the trolley wheel. The large strain insulators used in the tunnel are capable of working at 20,000 volts, and the porcelain links at 10,000 volts; either could be broken, therefore, without interrupting the service.

It was the aim to provide against the likelihood of failure due to electrical or mechanical trouble with the insulation; for this reason heavier insulation was used than heretofore, for lines of this voltage.

W. I. Slichter: It is to some of the minor features and problems of the designing engineer, that I would like to call especial attention. The principal characteristic which differentiates American from European railway installations is size. Our trains are about three times as heavy as the European trains, and our heavy traffic over single-track roads requires that every operation must be performed with the utmost reliability to prevent costly blockades.

In the locomotives under consideration it was necessary that there should be developed a tractive effort about three times as great as that developed by the foreign locomotives, and the practice of pushing a 2000-ton train up a 2 per cent grade required that this tractive effort should be applied gradually, steadily, and continuously, as any sudden variations in a tractive effort of this large value would almost certainly result in breaking a train in two and possibly in causing a wreck. Thus the control system of such a locomotive is a most vital feature. There can be no reduction in the tractive effort after it is once applied, and there must be sufficient control-steps so that successive increments of tractive effort are not so great as to slip the wheels or strain the draw-bars to a dangerous extent.

These conditions rendered any scheme of double-speed connection, such as concatenation or changeable poles, undesirable, as in these it is necessary to cut out at least a portion of the motors while the change is being made. In this particular case the character of the service and the low speed of the locomotive eliminated the necessity of having more than one running speed. The problem was then to provide a control system which would give a steady acceleration and yet provide for running at fractional speeds for short intervals of time such as 15 min., as contrasted with continuous running.

This is accomplished by using plain rheostatic control in the secondaries of the motors, varying the resistance by contactors and providing sufficient capacity in the rheostats to permit of running for 15 min. at full load. Of course this means that the locomotive takes full rated power from the instant of starting; but the percentage of power wasted in this way is not great, as the running time is long compared with the time occupied in starting.

The control system consists of fourteen contactors per motor, five of which are in the primary, there being one contactor on one phase and two on each of the other two phases to provide for reversing the motors. This leaves nine contactors in the secondary to give thirteen steps, which is accomplished by a scheme of dividing the resistances into two or three groups, each having its contactor; and these groups are brought into different combinations so that each group is used over and over again, some times in series, some times in multiple with the others, and not left idle after being used once.

Of course this involves increasing the resistances unequally in the three phases, but this unbalancing has been kept within such limits that the torque per ampere is never less than 90 per cent of that with balanced resistances on all steps, and this loss is of far less importance than the inconvenience that would result either from increasing the number of contactors or decreasing the number of steps. As Dr. Hutchinson has said, an additional step has been obtained by closing the circuit at starting on two of the four motors before the circuit of the remaining motors is closed, thus the tractive effort on the first step is about 10,000 lb. and on the second 20,000 lb. and while accelerating at an average tractive effort of 37,500 lb. the tractive effort may be kept within the limits of 41,000 lb. maximum and 35,000 lb. minimum.

A separate and independent set of resistances is provided for the secondary of each motor to avoid the tendency of the motors to exchange current and " buck " when they are all connected in multiple to one set of resistances. If the driving-wheels were of exactly the same diameter, this multiple connection would act as a side-rod and tie the motors together; but as there are apt to be inequalities in the diameters of the different driving-wheels, a considerable load might be put on the motors in merely slipping the wheels to make them revolve at the same speed. As it is, the only effect of the existence of driving-wheels of different diameters is to cause a slightly unequal division in the load on the motors, which may be cared for by the auxiliary resistance referred to by Dr. Hutchinson. At the same time the natural tendency of the wear is corrective, tending to wear most on the larger wheel.

The advantage of the induction motor, due to its peculiar adaptability to regeneration, is best illustrated in this instance by considering the amount of energy which is regenerated and which would otherwise have to be dissipated in rheostats. To hold a train having a gross weight of 600 tons on a 2.2 per cent grade would require a resistance capable of absorbing 650 kw. per locomotive for the time during which the braking occurred. This corresponds, in size of rheostats, to the condition of running continuously at a speed of 4 miles per hr. with an input of 460 amperes per motor and a tractive effort per locomotive of 37,500 lb.

A very prominent feature of regeneration with the polyphase induction motor is the simplicity of its operation. As the greater part of the train gradually passes the summit and comes upon the down grade the speed gradually increases from 15 miles per hr., to 16.5 miles per hr., and without any attention on the part of the motorman the locomotives change their function from motoring to generating and from taking 1000 kw. from the line to giving back approximately 600 kw. Meantime there has been a tendency on the part of the generators in the power house and the water wheels to increase in speed with the speed of the motors on the locomotive.

This tendency is made use of by means of a centrifugal device to throw in circuit the water rheostat mentioned by Dr. Hutchinson, and located just outside of the power house. This rheostat takes the energy generated by the motors and holds the speed and frequency of the system down to normal. The water box is controlled in such a way that with a very slight increase in speed of the water wheels or generators the resistance is thrown across the generator bus-bars. When the speed has become constant the resistance in circuit remains constant, and, conversely, as the speed decreases the resistance is drawn out of circuit. With a growth of the system and increase in the number of locomotives operating at once, this rheostat in the power station would be used less and less and more of the regenerated energy would be usefully employed.

E. F. W. Alexanderson: Looking at the design of the motors on the Great Northern locomotive as an induction motor, nothing new is to be found except in the proportions. In order to meet practical railroad requirements the mechanical clearance is three times as large as is usually made in a stationary motor of the same type, and twice as large as it has been made in certain well known three-phase European locomotives. As illustrating that the predetermination of the characteristics of induction motors has become almost an exact science, even when the proportions do not allow their derivation from other existing machines, it may be mentioned that the characteristic curves and overload capacity of the motor from test agree within the errors of measurement with the data submitted with the contract.

The interesting part of the problem in this case is the adaptation of the induction motor to railway requirements. The motor, as mentioned in the paper, considerably exceeds the specifications of capacity in continuous operation for a given temperature rise. In the case of a stationary motor of the ordinary kind, such a result would be a criticism of the design. With a locomotive motor it only emphasizes a fact borne out by experience in several instances, that the success of an electric locomotive depends more upon a certain balance of design than the ability to meet a definite service requirement; in other words, the maximum tractive effort of the motor must have a certain relation to the weight on drivers, and a locomotive motor that lacks overload capacity would be unsuitable even if it should meet the specified requirements in the most creditable way. Railway motors of the ordinary type are in most cases limited in capacity by the temperature-rise in service; this is substantiated by the fact that there is allowed a higher temperature than that found economical with stationary machinery.

The continuous capacity of such motors of the closed type is usually about one-third of the capacity for one hour, whereas, the continuous capacity of the Great Northern motors with forced ventilation is 79 per cent or 74 per cent of the hourly capacity at 500 volts and 625 volts respectively. In attempting to meet the Great Northern requirements, it was immediately apparent that a motor of any reasonable size would run too hot unless forced ventilation were used. It was naturally attempted to make the artificial cooling as efficient as possible by taking advantage of the structure of an alternating-current motor with distributed windings, thus bringing the air into intimate relation with the active parts. In order not to waste space in the length-direction of the motor—which had already been encroached upon by the double gearing—the air is led through holes or channels running longitudinally through the core. This system of ventilation proved successful, and the tests show that the continuous capacity with forced ventilation is practically the same as the hourly rating on a standard basis without ventilation. It is most gratifying to see in Dr. Hutchinson's analysis of operating conditions that the design is well balanced, and that the continuous capacity is in proportion to the maximum work the locomotive may be called upon to do with a given weight on the drivers.

The weight-efficiency of the three-phase railway motor is often referred to. It might, therefore, be of interest to compare the Great Northern motor with two other well known locomotive-motors—the Detroit River tunnel locomotive (a freight locomotive of the same weight and mechanical design provided with four motors of the double geared type), and the Simplon, a well known three-phase locomotive. In the same table is shown the comparative figures for a stationary three-phase motor of the same dimensions. All three induction motors have practically the same armature peripheral speed, and the weight per horse-power is favorable. The Simplon motor is favored by a small air-gap, but handicapped by being wound for high voltage. No data are available for another three-phase railway motor with forced ventilation, but the capacity at 40 degrees rise of the Great Northern and the stationary motor gives a sufficiently good comparison. As might be expected, the weight per horse power in this case is somewhat greater for the railway type of motor on account of the air-gap being more than twice as large. The comparison of the four-motor types shows a relative consistency and also indicates the great possibilities of the inductive motor for high continuous output.

	Detroit River tunnel 600-volt direct current	Great Northern 625-volt three-phase	Simplon 3000-volt three-phase	Stationary motor 550-volt three-phase
Weight..............................	8330	12200	22000	11500
Air-gap..............................		0.125	0.059	0.050
Peripheral speed in feet per minute....	2450	3440	3250	3550
Horse-power hourly—75 degree rise....	300	550	1100	——
Weight per horse-power...............	29.5	22	20	——
Horse-power continuous—75 degree rise.	—	400	—	——
Weight per horse-power...............	—	30.5	—	——
Horse-power continuous—40 degree rise.	—	260	—	330
Weight per horse-power...............	—	47	—	35

C. L. de Muralt: I am one of those who desire that each system shall have a fair show. I do not propose to advocate that any one system shall be used exclusively. The three-phase system has advantages which have already been thoroughly appreciated, and which will be more appreciated the more it is used, and I think it will be used extensively. But the other systems have also their advantages, and these systems will no doubt be continued to be used. It is for the broad-minded man to understand and realize and appreciate the advantages and disadvantages of each system. Engineers, in considering the electrification of steam railroads, must decide which system presents the greatest number of advantages and the least number of disadvantages in each particular case. There is no such thing as a universal system. There is no universal steam locomotive now. We might as well put forward one type of steam locomotive to haul all of our steam trains, as to put forward any one electrical system for hauling all our electric trains.

What Dr. Hutchinson brings out principally, to my mind, is that the efficiency of the three-phase system is extremely high. I have claimed that for some time, but have met many doubters. We have now an American example which shows conclusively that I actually underestimated the efficiency of the three-phase system. There is no other system that will show the same efficiency under the same conditions.

The recuperative feature has also been rather underestimated by me. Dr. Hutchinson's paper shows conclusively that the regeneration of the trains on the down grade is fully up to the calculated results. There is, of course, no reason why actual experience should disagree with calculations on this subject. But the full commercial value of recuperation has not been brought out. It cannot, because this is too limited an application of electricity. When the road is extended and operates over a longer distance it will show this also. In Europe, where roads are operating over long distances, with several trains on the line at one time, good use is made of the recuperative feature. Many mountain roads in Switzerland do not need any thing like the amount of energy that would ordinarily be required to propel the trains up-grade, because the power returned by the trains descending the grade helps out the power station.

Some engineers claim it is not good practice to use two trolleys. Unquestionably, one would be preferable; but two are used, and have been used for years, under conditions where switches are placed as close together as the tracks will permit, and these trolleys have been operated successfully. It is not an operating feature at all; it is a matter of suitable design, and proper location of overhead line. Once these are taken care of, the road will operate with two overhead wires just as well as with one. There is hardly any difference in maintenance either, because the maintenance cost is made up of labor rather than of material, and the same track-gang that must be kept waiting to take care of an occasional break on a one-trolley line will also take care of an occasional break on a two-trolley line.

The constant-speed characteristic is of course an engineering question, a question that needs to be carefully investigated in each particular case. It will not do simply to say that the series characteristic is advantageous. It may be so in many cases but not always. Sometimes it is disadvantageous, and for main trunk line operation I think it generally is disadvantageous. It is all very well to say that the constant-speed characteristic means increased power when the train runs at full speed upgrade. But those who have ridden up hill in an automobile, and watched the automobile slow down until it stopped, will want a constant-speed machine for grade work, and not a variable-speed machine. Of course when the locomotive does not do its work, it does not use any power. But the amount of energy consumed by a train running at slow speed and using small power, is not one whit smaller than the energy consumed by a train running at high speed and using big power, because the big power will be used for a shorter period only.

Calvert Townley: One point has not had as much emphasis as its importance deserves. The advantages of electric over steam traction and the possibilities of using mountain streams to supply electric power to the Western railroads have been much discussed on paper. Here is a case where the installation has actually been made. A large steam railroad, backed by abundant capital, and officered by men of high professional standing has electrified a section of its line at heavy expense. The type of apparatus selected, its performance, and characteristics, in which we, as electrical engineers, are natually much interested, important though it may be, is really secondary. The greatest importance attaches to the adoption of electricity to replace steam in this sort of service for the first time. It means more than any mere question of the electric system selected. We hope that this installation will be successful; that it will be extended; that the road will find the substitution of electricity for steam has been to its advantage; and that not only because of operating economies but also on other and broader grounds the value of this installation will prove to be so great that a distinct advance toward the electrification of important trunk lines will have been made.

I am personally pleased that we have at last in this country a three-phase installation for heavy railroad service, and from which we get such an encouraging report of early performances. The service requirements are well selected to favor this system, which certainly should do well here, if anywhere. It would be extremely unfortunate, both for those immediately concerned, as well as for every one else interested in the electrification of steam roads, if such an installation should partly or wholly fail. The railroad world is quick to note success or failure, but slow to differentiate between systems or to accept explanations from interested parties.

Some matters in the paper are not entirely clear. First, what is the actual capacity of this locomotive? I note that the guaranteed performance of the motors before they were built was 250 h.p. each under continuous load, while after construction the tested capacity was 375 h.p., an increase of 50 per cent. In making this statement the author permits us to infer that there is a corresponding increased locomotive capacity. In another part of the paper, however, the transformer capacity is said to be smaller than that of the motors. The transformer rating is given at 400 kw. each, there being two supplied. If the transformer is limited to its rating, the continuous output of the motors cannot exceed 200 h.p. each, due allowance being made for losses; that is to say, 7.64 h.p. per ton total weight of locomotive. Even if the transformers can be made to carry 25 per cent overload continuously, and thereby permit the motors to be rated at their guaranteed capacity of 250 h.p. each, the horse power per ton becomes only 8.7, not as great as can be obtained with, for example, 25-cycle, single-phase motors. In view of this fact the author's second advantage of a greater continuous output than with any other type of motor would fail of demonstration. Further, if the tested capacity of the motors, 375 h.p. each, is to be made available, apparently the transformer capacity must be very materially increased. Additional or larger transformers probably mean a larger cab, heavier framing, and so on, and this of course changes the weight and upsets any direct comparison. It is not stated that the control apparatus, switches, and resistance are large enough to handle the current for motors rated at 375 h.p. each, or that the blowers have sufficient capacity to furnish additional air to the transformers. If these matters have been covered by tests, a statement regarding them would afford a better understanding of the claim for great power per small weight.

The claim for maximum electrical and mechanical simplicity is valid as applied to the induction motor, which should receive full recognition. However, the control apparatus, compared with that required by direct-current or by single-phase motors, is much more complicated. It is necessary to break twice as many circuits as with direct-current or single-phase motors. Instead of being more simple, therefore, the control part of the three-phase equipment would naturally be somewhat more complicated.

With reference to uniform torque, I ought perhaps to say that our observations on single-phase locomotive performances do not support the view that the so-called pulsating torque of that motor is practically in evidence.

Since practically all the single-phase installations in this country use the 25-cycle current, the author's claim that the three-phase system has an advantage because it alone can use this frequency is somewhat puzzling.

The comment of a prominent steam railroad engineer on the question of constant speed was that the conditions which affect the operation of trains on schedules and which cause delays are many of them entirely foreign to any question of traction. Various and diverse influences cause delays, requiring trains to make up time if they are to be maintained on schedule. Therefore, an inflexible and a uniform speed is undoubtedly somewhat of a disadvantage even though the running time and operating conditions indicate that ordinarily it is desirable to maintain a uniform speed when the trains are running.

Ability to regenerate current by the three-phase system is of an undoubted advantage, and, naturally, will be used to produce a saving as the system is extended beyond its present limitations.

Charles P. Steinmetz: More than 15 years have elapsed since three-phase induction motors were first applied to railway work. Some years previously the single-phase commutator motor had been designed for railway work, but had not been used in practice, because there was no frequency low enough to make that type of motor suitable. A great deal of work was done on three-phase induction motors, a number of equipments were built, and high hopes were entertained that we were at the beginning of important developments in electric railroading. At the same time the synchronous converter was successfully developed and applied, its use enabling the operation of direct-current railway systems over such distances that the direct-current railway motor took care of all railway work for many years. For this reason the three-phase induction motor railway development did not progress in this country as it was hoped it would. The three-phase motor was used only to a limited extent, in mining locomotives, etc. Abroad, where prejudice retarded the introduction of the synchronous converter, considerable work was done in three-phase railroading.

Ten years after the early work the alternating-current railway motor was taken up again and the old single-phase compensated commutator motor was introduced industrially. Meantime it has developed so that to-day the single-phase motor is successfully applied to the solving of electric railway problems. At the same time most of us have begun to understand its limitations; it is not a universal motor, as its application is seriously circumscribed. The need of a frequency lower than the present standard as claimed by many designing engineers, limits the use of this type of motor. If it requires a system that differs from standard in all its parts—generators, transformers, etc.—this motor will be handicapped, because the economic development of the electrical industry must be towards uniformity in methods of generation, transmission, and distribution of power.

It seems now that the three-phase induction motor also has reappeared and found successful application. The advantage of this type of motor is its simplicity and reliability, its uniform torque, and greater output for its weight. These are the characteristics of polyphase machinery. The main characteristic of the three-phase induction motor, however, is that it is a constant-speed motor. From this feature follow most of the other characteristics: the relatively low efficiency of acceleration; that it consumes the same power in turning round slowly as when running at full speed at the same torque. A result of the constant-speed feature is the automatic regeneration of power above synchronism. We can improve the acceleration by concatenation, or, as it is called abroad, cascade connection, or by changing the number of poles. The repulsion motor or any alternating-current commutator motor can be made regenerative, but this means additional complication, which to my mind is undesirable in railway work.

The constant-speed feature limits somewhat the general application of the three-phase motor to railway work. It is well suited for mountain divisions, for running continuously with heavy torque, positive or negative. The successful application described by Dr. Hutchinson is on a mountain division. Another application would be for very high speed passenger service. At speeds of 50 or 60 miles an hour, or more, the air friction produces a considerable part of the train resistance; there is a decrease of the difference between the power required to run on a level track at a constant speed and the power of acceleration, and, therefore, an approach to the same conditions as running on a mountain division.

For general railway work, however, as at present carried out in this country, the three-phase locomotive is not as well suited as the direct-current locomotive or the single-phase locomotive, for the reason that the direct-current series motor or the alternating-current commutator motor can directly replace the steam locomotive in present railway operation, while the three-phase induction motor locomotive is not at its highest efficiency, when operating on a railway system under existing conditions. The method of operation must be rearranged to a constant-speed service. Whether the constant-speed operation of the railway would be disadvantageous, or advantageous, over the present variable-speed method, requires further consideration. At present we are inclined to consider it as a disadvantage; the present varying speed method as preferable. If the steam locomotive slows down on an up-grade, or loses time at a station, it can make it up on the level track by speeding. At the same time, if the traffic is unusually heavy, the steam locomotives cannot make schedule and all schedules are upset, and just when we need the full capacity of the railroad system most, the operation of the railroad is at its worst, as we have seen more than once.

In a broad study of the railway problem we have to investigate whether the method now in use is really inherent in the problem, a necessary requirement of the desired results, or whether it is an incidental feature of the particular apparatus we use. The steam locomotive is a constant-power motor. It gives approximately the same power irrespective of the speed, the power as limited by the steaming capacity of the boiler. Whether there is a heavy grade or a run on a level, there is a definite power limit, and this condition has brought about the present method of railway operation. It was the necessity of making up for lost time, as the locomotive has to slow down on up-grade, because it can not keep up steam when running as fast on a grade, as on a level track. With a different type of motive power, however, it would be well to investigate whether there would not be an advantage in rearranging the method of operation to suit the characteristic of the new motive power. It is quite likely that the capacity of any railway system could be greatly increased if we could get really constant-speed operation irrespective of grades, loads, etc. Possibly at constant speed much greater passenger traffic and much greater freight traffic could be handled. All these problems require impartial investigation by engineers that are not in favor of any one type of motor, or of the steam locomotive; engineers that would consider the entire railway problem, and find a solution for increasing the capacity of existing steam roads.

As regards the limitation of the shunt motor, I wish to draw attention to one particular feature: when we speak of the shunt motor, or the induction motor, we always exclude the rapid transit service, from its field of use. We consider rapid transit as that class of service where the series characteristic is especially necessary and to which the shunt motor is especially unsuited. The most extreme case of this intermittent service, acceleration at heavy torque and no constant speed running—the most extreme case of rapid transit—is the high-speed passenger elevator. This service is now always operated by the induction motor and the shunt motor, with or without compound field. It is rather interesting to see that where no precedent limited the character of operation, in the extremest case of rapid transit, motors of shunt characteristic have been chosen for the sake of service capacity, reliability, and safety.

Carl Schwartz (by letter): The operating conditions as presented by Dr. Hutchinson seem to indicate that the three-phase system is well adapted to the service, its few inherent disadvantages being overbalanced by its advantages.

In previous considerations of various systems of electric traction considerable attention was given to the design of the locomotive, the characteristics of the motors, and comparatively less to transmission and generating systems. While the locomotive is a very important part of the whole, both the weak and the strong features of an electric traction system are only in part determined by the characteristics of the locomotive. The decision as to which system is best to adopt may be influenced very much by other considerations.

One of the first advantages of the three-phase system in common with the direct-current system is that the generators are not subjected to such extremely heavy strains as are incidental to single-phase operation. In case of the Great Northern Railway Company's electrification current is generated at 6600 volts, transformed at the power house to 33,000 volts, this pressure is reduced at the substation to 6000 volts, and fed to the trolleys and the track rails. The intermediate transformers are a very important element in the system, and, together with the fact that the system is three-phase and not single-phase, explain the freedom from generator troubles.

Under present conditions we understand that one important feature of the three-phase system, the recuperation of energy from trains going down-grade, cannot be taken advantage of. This advantage, of course, exists only if trains are in service simultaneously up- and down-grade, so that there is load to carry at the switchboards for the train going down grade and returning power back to the station. This condition can ordinarily only be met by an installation of sufficient size, unless the schedule is so arranged that trains will travel up- and down-grade simultaneously. If this is not the case the power returned by a train running down-grade will have to be absorbed by automatically regulated rheostats which thus simply replace the mechanical brakes on the locomotive and dissipate the energy.

I investigated in detail sometime ago the merits of the three-phase system for a tunnel electrification in the Middle West where no water power was available. I found that the same conditions eliminated the feature of power recuperation, and, in this case, the only reason remaining for possible selection of the three-phase system. The result was the selection of direct current with a storage battery to equalize the load.

The operating conditions in the generating stations are stated to be very irregular. The generators may carry full load for, say 15 minutes and then run idle for several hours. Outside of bad regulation the objections against such intermittent operation are not great, but the operation would become extremely wasteful in case of a steam generating station and would show results on the coal pile that would exceed the consumption of the Mallet type locomotive.

Dr. Hutchinson calculates the equivalent consumption of a Mallet compound locomotive at 8 lb. of coal per kilowatt-hour. In case of the three-phase system he assumes 3 lb. of coal per kilowatt-hour at the bus-bars, or 4.28 lb. at the rail, taking the total efficiency from the station bus-bars to the rail at 70 per cent. The consumption in a modern steam station is two or three pounds per kilowatt-hour for a load-factor of, say, between 60 per cent and 40 per cent, but not for operating conditions similar to the Cascade Tunnel electrification. I do not desire to predict any figure for coal consumption in this case, but it will be above 8 lb. per kilowatt-hour, as in the case of the steam locomotive, and not below.

Any other system than the three-phase would under the same conditions not show better results, as the question of coal consumption is influenced more by the load characteristics than by the few per cent difference in efficiency between rails and station bus-bars. The traffic will have to be materially greater to approach a consumption of, say 3 lb. of coal per kilowatt-hour or one-half that of the Mallet compound locomotive.

Dr. Hutchinson has enumerated under the disadvantages "the constant speed of the locomotive" but he himself sees this characteristic rather as an advantage. Constant-speed characteristics of the locomotive motor on a mountain division is apt to accomplish one thing which other systems than the three-phase will not do; that is, allow close adherence to the schedule, which can be made more uniform than for steam service. While there is no possibility of making up lost time there is less possibility of losing time. As the speed is limited by the amount of traffic possible to handle up-grade on the division, the average speed will be increased. This means a proportionate increase in the capacity of the road and may in some cases eliminate the necessity of double-tracking.

Some of our Western roads may find this feature a sufficiently strong impetus to induce them to electrify, even if the power house should not show one-half the coal consumption of the Mallet type of locomotive. Furthermore, this item of energy consumption, as far as station economy is concerned, disappears more or less if water power is used. The only feature remaining is some possible increase in capacity of the power and transmission system, which may not be too expensive on account of the short duration of the peaks.

The three-phase system installed for the Great Northern railway by Dr. Hutchinson is the first three-phase railroad electrification in America, and there seems good reason to believe that this example will go far to secure for the three-phase system in this country the place it deserves.

Frank J. Sprague (by letter): The present is no time for arbitrary statements as to the supremacy of any one electrical system, but rather for that catholicity of view which admits of a variety of effective solutions for many problems, even if for others some one system may offer a preponderance of advantages. I shall, therefore, express no special views on the relative merits of different systems, except that I am glad to note that my efforts in behalf of the adoption of interpole motors and 1200-volt, direct-current operation, with both overhead and third-rail conductors as one of the possible alternatives, have received the practical endorsement of adoption and a rapidly widening application, thus giving the electrical engineer an additional lever for attacking the electrical transportation problem on a large scale.

Without discussing earlier installations, it is of interest to note that so far as at present developed this Cascade Tunnel installation is one of three in this country of almost identical requirements; that is, operation through a tunnel of heavy freight and passenger trains on severe grades at moderate speeds. Each of these is characterized by a different electrical system. Two, the Sarnia single-phase and the Cascade three-phase, are in operation, while the Detroit Tunnel direct-current locomotives have been fully tested. In each case the steam locomotive could only be used under the maximum disadvantages, the very worst possible conditions. Adoption of electrical operation by almost any method offered an effective remedy, and it is an encouraging fact that each of these installations overcomes many difficulties incident to steam operation under certain limitations, and that we have as a result higher speeds, greater capacity, and increased safety and cleanliness.

But none of these installations represents trunk line requirements under conditions which exist on many of our roads. It has been my fortune to have for nearly three years made a study of such a trunk line, presenting what I consider perhaps the most difficult operating problem I have ever encountered. I refer to a stretch of nearly 140 miles on the Sacramento Division of the Central Pacific Railroad, over the Sierra Nevada Mountains. There is much about the investigation of this which it would not be proper for me to touch upon, and I will only refer to it in a brief way.

The section in question is normally single tracked, with sidings every few miles which raise the aggregate trackage to something over 200 miles. The physical conditions are such as to present extreme difficulties to double tracking, although second tracking is being added for a part of the distance. There are nearly 32 miles of snowsheds and tunnels, and in winter the snow sheds form practically continuous tunnels. The grades are severe, there being a rise of about 7000 ft. in 83 miles in one direction, with a ruling grade of 2.4 per cent, and the amount of curvature is startling.

Over this division practically the entire freight and passenger traffic from the Union Pacific Railroad for Central California passes. Freight trains, often over a third of a mile in length, and with 2000 to 2500 tons trailing load, are operated in both directions. These trains require as many as four consolidated locomotives, or two of the heaviest Mallet compounds. The running speed is sometimes as low as seven miles an hour, and the schedule speed for the division is seriously interfered with by opposing traffic. Coupled with this freight operation is passenger operation in both directions, in trains up to nearly 400 tons trailing load, way trains, "limited," Pullmans, and fast-mail trains, operating at double the freight speeds, and with coasting speeds as high as 50 miles an hour.

This division is approaching the limit of steam capacity, especially when considered in relation to the balance of the system, and the question is whether such a division can be operated electrically, and if so, what can be gained thereby. Would the object be economy in fuel? Such alone would not warrant electrification, although the general line of investigation of railroads operated by electricity will show about 50 per cent in coal economy. If carried out, electrification will be primarily for the purpose of increasing capacity, and thereby effecting ultimate economy.

The specifications already issued require operation on this road of 2000-ton trains at 15 miles an hour on a 2.4 per cent grade, and 400-ton passenger trains at twice this speed. This last condition involves a much larger motor capacity at the head of a passenger train than the gratifyingly large capacity exhibited by the locomotives of the Cascade Tunnel, not in tractive effort, but in the product of tractive effort and speed.

The investigation of the possibilities of electrification on this road have been conducted on a plan somewhat different from that ordinarily taken. It was not deemed wise first to decide upon a system, but rather to ascertain the costs of locomotives by various systems which could perform a service determined as essential to effective operation, and then to collate all the facts, advantageous and otherwise, affecting capital cost and cost of operation, after which the best system to meet the existing conditions could be determined.

If asked what system would probably be indicated, I must frankly say that I do not know. That electrification is possible I do know, and that such can be successfully carried out I do not doubt, with increased capacity and general economic results. That it will be so done I also firmly hope and believe, but I am impressed with the absolute necessity that in considering a problem of this character, as well as all problems which are continually confronting the electrical engineer, there is no development which can be reasonably undertaken which should be curtailed, and none which should be disregarded.

We are passing through that inevitable stage of development and elimination essential to final correct decisions and permanency of results. However critical, therefore, I may sometimes feel as to the inadequacy of any system in some particular application, I welcome every installation which promises to further the effective and economic application of electricity to trunk-line operation.

DISCUSSION AT MINNESOTA SECTION, NOVEMBER 18, 1909.

Edward P. Burch (by letter): The writer made a study of the Cascade Division of the Great Northern Railway, including the Cascade Tunnel, and reported on its electrification to the Great Northern Railway Company, in January, 1904. The report was on the power problem, the mechanics involved, the available water power, the advantages of electric traction to prevent congestion of traffic, and finally on the net saving which was possible. The latter was corroborated by the record made by the general manager. It was recommended that a commission be appointed to study the subject as the responsibility for selecting a definite electric system for the whole division was large. The only precedent for the work was at the Baltimore and Ohio Railroad tunnel, where there were hauled many more freight and passenger trains per day up heavy grades and with great satisfaction, after the third-rail was installed.

The electrification of the Cascade tunnel itself was an exceedingly simple piece of work, but the electrification of the Cascade Division from Leavenworth to Everett, 109 miles, involved many problems not yet solved. The electric system and the locomotives were to be suitable for, and interchangeable on, the entire division, not for the tunnel only.

It was well known that no electric system was offered by American manufacturers for real railroading on these mountain grades; and experimental work was not welcomed on so large a scale. President Hill's decision was that the new Mallet compounds should be tried out.

The great objection to the use of three-phase power for railroad work is due to the necessity of carrying two overhead conductors; nor is this a minor matter in railroading. The delivery of power from a contact line to the locomotive is of vital importance and must be made absolutely perfect. Two overhead conductors in railroading, around freight yards and terminals, do not promote simplicity. It is not possible to carry two overhead wires with a difference of potential of 6,000 to 11,000 volts, above the many switches at yards and sidings which are most common in railroading, and make a rugged construction. Long, expensive, and complicated section-breaks are not desirable.

In practice the alignment of American track is not good. Further, the distance between the rail and the trolley of American roads will be from 22 to 24 ft. as a minimum, where European practice shows from 14 to 18 ft. Track irregularities cause the deflecting force at the upper end of the pantograph or trolley wheel to vary about as the square of the height. In railroading it will not do to have the trolley flop off, partly because it will be dangerous in ordinary operation. When there are two or three locomotive units to a train it is absurd to think that locomotive men will give attention to four trolley poles, turning them when the direction is reversed. A pantagraph is necessary, but it is not possible to run a pantagraph over rough switchwork at good speed without danger of short-circuiting the two trolley wires. A difference of potential of 6,000 to 11,000 volts will be used in heavy electric traction.

Modified systems may be used for mountain grades; namely:

1. The use of two trolleys for slow, three-phase freight locomotives; and the single-phase system, using one of the two overhead trolleys, for passenger service, for simplicity, variable speed, and rapid, efficient acceleration.
2. A single-phase, 11,000-volt trolley line and a rectifier on the

locomotive delivering 600-1200 volts direct current for motors. This would make an interchangeable system.

3. Three-phase generation, single-phase utilization from a single contact line, and the H. Ward Leonard scheme with the high-voltage, high-speed, light-weight, single-phase motor-generator which will drive the axles through intermediate low-voltage motors.

4. The use of the three-phase system with two trolleys for heavy grades, and the use of three-phase motor as a single-phase motor from one trolley at all sidings, yards, terminals, shops, etc., in slow speed and light switching work, for simplicity and safety.

Max Toltz (non-member): In regard to the details of the electric locomotive. Transmitting the power by gears from the motor to the axle is street railway practice and is not as good as side-rod construction. The gear transmission with which the Great Northern electric locomotive is equipped makes it unhandy to inspect the apparatus, or to repair motors or to inspect accessories, because it will be necessary to lift the cab and pull the truck from under and then raise the motor, etc. With the side-rod construction smaller wheels can be used, and, instead of four motors, two motors need only be installed above the locomotive frame. This has also the advantage of locating the collector rings where they can easily be inspected and repaired.

The motors should be wound for at least 3000 volts, instead of 500 volts and the former voltage should be also carried by the trolley wires. In that case the transformers on the locomotive between the trolley wires and the motors would be eliminated—a step towards simplification—and at the same time the electrical losses due to transformers will be cut out.

Instead of trolley poles with wheels, bow trolleys with roller contact for each wire could be used having the advantage of overcoming the present trouble of the trolley wheel jumping trolley wires when going in either direction.

An automatic device similar to the one used on the Valtallina electric three-phase locomotives should control the current supply to the motor instead of the common step-down rheostat.

A single speed in the motors is satisfactory for the tunnel operation, but if the whole Cascade division is to be electrified two speeds will be necessary, so that trains going down grade may run at a higher speed.

The transmission lines between the power house and the substation would be more reliable if each circuit had its own pole line, one on each side of the railway, for a slide or a falling tree would not put the line completely out of commission.

Trolley wires suspended from messenger cables would withstand harder usage in heavy operation.

In regard to some of the data given in Dr. Hutchinson's paper, exceptions should be taken. The rail resistance is given at 6 lb. per ton, which under the very best of conditions of rail and equipment is 6.5 lb. Dynamometer tests give 6.5 to 14.25 lb. per ton. In the tunnel with its soot and wet rails the resistance used to be over 10 lb. per ton.

The rail resistance of the Mallet locomotive is stated to be 47 lb. per ton, computed from ammeter readings. This figure is much too high, and is probably due to the air pump action of the pistons in the cylinder. It is assumed, of course, that the throttle valve was closed with the reverse lever being in the forward corner notch. It should be borne in mind the cylinders of the Great Northern Mallet locomotive have no by-pass connection, but are equipped with valves, one at each end of the cylinder.

The following results were obtained from tests in which indicator cards were taken simultaneously on all four cylinders of the Mallet, on a level track:

Type of locomotive	Locomotive weight	Miles per hour	Horse power absorbed	Resistance lb. per ton
Mallet	250 tons	8	57 h.p.	10.8 lb.
"	250 "	10	74 "	11.2 "
"	250 "	12	95 "	12.7 "

If Mr. Emerson had given the coal consumption per 100 ton-mile-hours instead of 100 ton-miles the results would have been somewhat different. The writer assumes, therefore, that Dr. Hutchinson's calculations are based upon a speed of 7 to 8 miles per hour, but calls attention to the fact that the most economical work of the Great Northern Mallet is performed at about 11 miles per hour.

The minor advantages of electrification as explained should be called " major " advantages but to these should be added:

1. The saving in locomotive ton-miles due to the elimination of the tender of the steam locomotive.
2. The mileage of the electrical locomotive will also exceed that of the steam locomotive, because the engine need not go to the round house for boiler repairs and need not be turned.
3. The best showing of the electric locomotive as compared with the steam locomotive will be made during the extreme cold weather when the latter will fail in generating the usual quantity of steam, while the former will not be hampered by any temperature prevailing in this country.
4. Also the elimination of all water and coal stations should not be overlooked.

The steam locomotive cannot expect to equal the record made by the New York Central locomotives of only 14 minutes delay in 80,000 train miles.

E. Marshall (non-member): On down-grade through the tunnel the crews were at first afraid to trust to regeneration by the induction motors to do the braking, but a few trips were sufficient to reassure them. The trip through the tunnel is now entirely devoid of danger from this source.

There have been only a few failures due to the electric locomotives. In one case some of the resistance grids were burned out, but the locomotive could be operated. In several cases of overloaded motors the secondary leads of the motors were melted from the rings. Due to inaccessibility the repair of these motors is a difficult task.

The system of current collection by means of a wheel trolley and overhead wires strung similar to street railway lines is not satisfactory. Trolleys leave the wire, tear down the overhead work, and sometimes are the cause of a train breaking in two, due to relieving the load on the locomotive. In case of change of direction the trolleys must be changed; this is sometimes forgotten and the overhead construction suffers in nearly every case. On account of the 5 ft. spacing of the wires in the open, and 8 ft. in the tunnel, the pantagraph cannot be used. It is probable that the overhead work will be changed to catenary construction and bow collectors used, as there is no question about that design being more satisfactory.

On the whole the operation of this system is most satisfactory. The above remarks are not made as criticisms but are mentioned to show that the defects are no greater than one has a right to expect in a system where precedents are so few. Everyone connected with the operation of this system is anxious to see it extended to take in at least all of the track having the 2.2 per cent grade.

Cary T. Hutchinson: I am gratified to see that there seems to be a very general agreement with me that the three-phase system was well adapted for use in this particular place. I believe nearly all of the speakers have assented to this.

I find in the discussion a number of points in which the various speakers differ from me in regard to details, and it is very probable that they may be right and I wrong. I do not think it necessary to discuss these points, but wish merely to answer the questions that have been asked.

In reply to Mr. Katté. The ground wire was omitted as there is no lightning on this side of the mountain. My reasons for saying that probably a three-phase system would have been used even though only the tunnel were under consideration, was because of the far greater capacity of three-phase motors as compared with direct-current motors in the same space, and the lesser cost of construction and operation. Wooden poles were used, as they could be obtained very cheaply and of extremely good quality.

Mr. Arnold and others question the high frictional resistance of the Mallet locomotives. I can only say that these tests were carefully made by competent observers, and I am sure are accurate expressions of the conditions that existed. I of course do not pretend that the internal losses of the Mallet, when operating under its own steam, are represented by these figures; there is no direct comparison between the two conditions.

I do not think that the method of control used on the Italian State Railways referred to by Mr. Waterman would be satisfactory under the conditions of a Western railroad in this country where it would be fatal to install any apparatus requiring careful supervision of operation and maintenance. Everything must be of the sturdiest character, and as nearly as possible "foolproof."

Mr. Pomeroy gives some very interesting results of coal consumption of heavy locomotives on mountain grades. It should be noted that Mr. Pomeroy shows the coal consumption to be nearly twice as great as I deduced from Mr. Emerson's statements, amounting to from 13 to 19 lb. per kilowatt-hour as compared with 8 lb. Mr. Pomeroy also brings out the very interesting fact that the coal consumption in operation is just double that deduced from test results. I had also arrived at the same figure by the comparison of records of operation with special test runs made on hills—such runs are practically of no value in determining coal consumption.

I agree with Mr. Smith and with others who state that the collection of the current is a very important factor in deciding the type of machinery to be used. The use of the trolley wheel in this particular case was forced upon me, and was not my deliberate choice, as the officers of the road would not permit encroachment upon the overhead space in the centre of the tunnel. It is not at all improbable that some change may be made in this, particularly if the system is extended, and a pantograph may be used.

I am also glad to see that Mr. Smith, in common with others, approves the rating of an electric locomotive by its continuous duty. This seems to be the only sensible way to rate any piece of electrical apparatus, even though it is used in intermittent service. There will of course be all sorts of intermittent service, and the ratio between the actual service and the continuous capacity must be determined for each particular case. A motor, however, having a greater continuous capacity will, other things being equal, be the better motor for any service. Other methods of rating railway motors serves principally to conceal the facts.

Mr. Denneen has emphasized some of the reasons for the use of special features of the overhead construction. In this, as in other matters, I can only say that all the details of this subject were carefully considered.

Mr. Townley questions the continuous capacity of locomotives on the ground of the lower rated capacity of the transformers. It is true that the rating of the transformers is only 800 kw., continuous, with the quantity of air specified but the transformers have an overload rating of 100 per cent for one hour. For the service that the locomotives are now employed in, the transformers have ample capacity, and there is space enough either to install larger transformers in case they are needed for the extended service under contemplation; or what would be simpler, increase the quantity of air to these transformers. This has been done on test. There would be no difficulty by one or the other of these methods in making the transformers equal in continuous capacity to the motors and rating the locomotive at something over 1100 kw. continuous. The control apparatus has been operating regularly at much greater power, and there will be no difficulty at this point. The motors themselves are the limitation to the capacity of the locomotive—not the transformers, nor the subsidiary apparatus.

Mr. Schwartz is of course correct in stating that the coal consumption of a steam station, operating as the Tumwater station is now operating, would be much greater than 3 lb. per kilowatt-hour and might be almost anything. My comparison was not intended to refer to existing conditions but to the service as it would be when handling the entire traffic of this mountain division, and the traffic so arranged as to secure a reasonably good load-factor at the power station, which I regard as an essential to the electrical handling of any train service. In other words, when a division is electrified, the train dispatching must be conducted in accordance with the exigencies of the power station; the cost of any other method of dispatching will be so great that railroad officials will readily agree to this limitation.

If, however, Mr. Pomeroy's figures represent more nearly the coal used in steam service, as I believe they do, then it is not at all certain that a steam station would not give better coal economy, even if operating under as disadvantageous conditions as now exist at the Tumwater station.

Mr. Toltz gives some interesting figures for the frictional resistance of Mallet locomotives based on the indicated power in the engine cylinder. As I have said above, there is no necessary connection between the power so used and the power required to tow the same locomotive. I do not, however, think that much reliance can be placed on indicator cards, taken under the conditions described by Mr. Toltz. It is to be noted that the figure he gives for the total resistance of the locomotives, of say 11 lb. to the ton, is about the same as he states the rail resistance should be, which he gives at from 6.5 to 14.25 lb. per ton. The 6 lb. to the ton that I used was given me by the chief engineer of the railroad.

Mr. Marshall has referred to some accidents to the overhead structure, due to trolleys leaving the wire. This has been due largely to the impossibility of keeping this overhead structure in proper alignment, owing to the fact that little or no time can be found for working on this structure, on account of the exigencies of the train service.

Parker H. Kemble (by letter): The handling of traffic on railroads has now been a business and a study for some eighty years. Certain broad principles have been laid down and methods developed which are worthy of attention in discussing or selecting a method of electric operation. A change of motive power does not imply an overturn in methods. Electric power does mean larger loads, greater speed possibilities, and greater range in grades without change in weight of train or type of locomotive; in other words, improved tools for the use of the traffic manager. The broad principles remain as before. On a railroad system of varying profile, the present system provides locomotives of moderate weight and high speed for levels, heavier and slower engines (or else lighter trains for the same engine) for the moderate grades, and Mallet specials and pushers for the steepest ridges of the divides.

To handle this traffic, what does electricity offer? In the alternating-current division there are two main systems at present —single-phase and three-phase. These are of essentially opposite characteristics. Neither will fulfil all the requirements of railroad traffic over varying profile. Each is perfectly adapted to handle a particular grade or condition. In combination they fill all requisites.

As regards power stations they are identical; both generate three-phase, 25-cycle current at about 11,000 volts pressure; as regards transmission line, even where all the power would ordinarily be taken from one phase, the combination would require but one more transmission wire with the added advantage of a possible balancing of load. As regards contact line, the extra wire shown in the paper under discussion can be easily installed.

A modification of the single-phase pantagraph would be necessary, but that would be about all the change. On the levels and slight grades the single-phase motor with its high acceleration variable speed, and variable torque, complies with the traffic requirements. On the heavier grades another wire is strung over the track and the three-phase motor comes in to add its valuable grade-climbing abilities and safe down-grade speed control to the other.

It does not seem beyond the possibilities of multiple-unit control to imagine these two motors working together. At any rate, were the three-phase motor to be restricted to the role of pusher, the single-phase motor could surely carry its own weight. With the rapid progress in alternating-current motor design, a combination of types for certain profiles might be available.

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COMMENTS ON DEVELOPMENT AND OPERATION OF HYDROELECTRIC PLANTS

BY HENRY L. DOHERTY

INTRODUCTION

The object of this paper is to call attention to certain features of hydroelectric work deserving of more general or more careful consideration than they have had heretofore.

The writer is so situated that extended treatment at this time is impossible. If suggestions of value can be made, even though the treatment is incomplete, sufficient interest may be aroused to prompt such effort on the part of others as will carry these suggestions to a successful conclusion.

Work of value on this broad subject of hydroelectric enterprises can be done by the Institute which will result to the benefit of not only our members, but to the public as well. The writer will attempt to point out such work as, in his judgment, can be carried on to advantage.

THE VALUE OF WATER-POWER SECURITIES

There is probably no other class of securities which deserves so well the support of the public as those issued by companies owning and operating successful water power properties, and having a permanent and relatively non-competitive market.

Except for the possibility of further development in heat engines which will materially increase their commercial efficiency, thus tending to reduce the cost of power from fuel, all of our water power plants will tend to grow more and more valuable, as it is improbable that fuel will ever sell at a lesser cost, and more than probable that the cost will gradually increase. The reduction in first cost of heat engines, the increase of fuel economy, and the decrease in cost of repairs, are the only factors which will tend to lessen the market value of power from hydroelectric plants.

Almost every other class of industrial or investment property is apt to depreciate at a much greater rate, and be subjected to greater seen and unforeseen risks. For instance, business enterprises based on patents become less valuable as the patents expire; substitutes for manufactured commodities can often be found, or there may be developed other methods of manufacture which will prove more economical. As an exaggerated example, coal mining operations might be cited; the more coal is sold, the less the coal company has left for sale, unless new property is constantly purchased.

Compared with almost every other class of investment, a water power plant is far preferable. The source of supply is, in the main, perpetual, although in some instances somewhat modified by timber operations and changes in meterological conditions. Such modifications are, on the whole, more than offset by the possibilities of further power or irrigation developments which will provide reservoir capacity and make useful flood waters which have heretofore been unavailable for power.

THE RELATION OF WATER POWER DEVELOPMENT TO THE CONSERVATION OF OUR NATURAL RESOURCES

Probably the greatest stroke of statesmanship of the last national administration was the interest aroused in the conservation of our natural resources. Unfortunately, the efforts of the administration were either largely misdirected or very generally misunderstood in regard to water powers.

Immense amounts of power are daily going to waste. The tendency of the Federal Government, and of many of the state governments, seems to be directed toward obstructing rather than encouraging the development of water powers. This Institute can do valuable work in educating the public as to the restrictions which should be made and the encouragement which should be given to enterprises of this character.

The most pressing need in the matter of the conservation of our natural resources lies in the direction of conserving our various sources of fuel supply. Every undeveloped water power means a constant unnecessary fuel consumption.

Government, both state and national, should remove as far as possible every unnecessary obstacle to water power development. Rights of eminent domain should be given universally to water power projects. Encouragement, and perhaps direction, should be given which will insure the development of the greatest possible portion of the total energy available from our streams. Unintelligent engineering, or hampered finances, may result in stream developments which permanently limit the power production to a small fraction only of the total power which the stream might have been made to produce. For this reason, intelligent planning and engineering will play a most important part in the future history of the conservation of our natural resources.

COLLATERAL ENTERPRISES

Combination projects for both irrigation and power can often be made highly profitable where commercial success for either project alone would be impossible. It is therefore necessary that the engineer who has the responsibility of determining the value of prospective power developments should be proficient in the engineering of irrigation—and it is probably impossible fully to cover the field of hydroelectric engineering without knowing all of the essential details of irrigation engineering as well. This opens up to this Institute a necessary field of work which even now seems somewhat strange and a few years ago would have been entirely remote. Power and irrigation projects, wherein the power must be generated at one point and transmitted to another point and there provide irrigation by means of pumping, is alone worth serious consideration. As interruptions to supply due to long transmission lines are of relatively less importance in such service, it is possible to lessen the transmission investment and operate at distances which would be prohibitive for some other classes of work.

The present state of the art in electrochemical processes is a factor which makes possible the profitable development of many water powers. Still further developments along electrochemical lines may add materially to the value of water power projects which now have no available market. Special attention should be paid to processes which do not require a continuous supply of current, thus permitting the utilization of power from water which would otherwise run to waste.

THE UNFAVORABLE FEATURES OF WATER POWER ENTERPRISES AND THEIR OPERATION

Were we to assume that there is no risk in the development of water power projects, and that their operation has proved universally satisfactory, we should simply retard the correction of some of the difficulties which have been encountered. We have learned by experience that the cost of development often proves excessive and far beyond the estimates made by engineers enjoying good reputations. We have found that frequently the power expected has not been realized. We have found that transmission lines will not yield that reliability of service which can be secured from a steam plant generating at the point where the power is utilized.

Failure to realize expectations in regard to cost of development, amount of power to be sold, existence of market (or of market at the price anticipated) and reliable service, has played an important part in the retardation of development of water power projects. The treatment of any one of these disappointing features would alone furnish subject-matter for at least one, and perhaps many more papers. It is unfortunate that mistakes have been made and that anticipations have not always been realized. If, however, we are to learn by experience, then the broadest possible discussion of these subjects is to be desired. It would contribute much to the ease of developing the now unused water powers if these difficulties could be overcome, or if the public could be made to understand the degree of risk and the cause for the existence of the risk.

Generally speaking, there is no more reason why anticipations should not be realized in water power enterprises than in other enterprises, if the proper amount of investigation and preliminary work is done. Unfortunately, however, the engineering investigation to determine the cost of a hydroelectric power proposition, and the exact amount of power available, is often a very expensive matter.

Accurate determination of the power available can be made only from complete data, and such data are obtainable only as the result of measurements extending over a term of many years. Our water power projects are exploited on everything from prospectuses based on the most complete data for determining every feature of the available power, up to and including the prospectus based on absolutely no reliable data.

Bankers, underwriters, and investors have formulated various rules regarding water power propositions. One prominent banker gave me this rule:

> We will not consider a water power project unless, after doubling the cost, cutting the available power in two, and reducing the market price by 40 per cent it will still show interest on the bonds necessary to issue.

This was spoken more or less in jest, but it and many similar statements warrant the belief that except among professional engineers the same, or similar, fixed and arbitrary rules for determining the merits of new projects are apt to be used by all classes of people who are to furnish the money for their development.

There is no reason why water power projects, with reliable stream gaugings covering a number of years, cannot be estimated, as to cost of construction and earnings, to a degree of accuracy closely approaching that which now pertains to the construction and earnings of modern office buildings, or similar enterprises.

If fixed additions to cost and fixed discounts from earnings are to be applied to water power projects, then we are apt to have the condition that only the poorer projects will be developed. The less known about an undeveloped water power the more readily can an attractive prospectus be written, leaving more than ample margin for any arbitrary deduction; while complete knowledge based on a thorough, honest, and intelligent investigation bring the promised earnings to a point which would not permit of further arbitrary deduction—nor, in truth, is further deduction needed.

After a proper examination has been made of a proposed water power plant, where the behavior of the stream is a matter of reliable record for several years, an enterprise of this character can safely be undertaken on a very narrow margin of profit. If, however, the investing public is offered a proposition for which a return of 10 per cent is estimated by conservative operators, based on careful and complete investigation, while other operators offer investment in a project for which they promise 40 per cent, the 10 per cent proposition is apt to go begging, even though it be well known that the source of the 40 per cent proposition is not of a character to warrant the investment of real money.

A confused condition exists in the popular mind in regard to the marketing of power. The inability of the public to understand this matter has been a great obstacle in the development of power propositions—and in this matter the electrical engineering fraternity has been more or less to blame. Cost of power is sometimes figured and stated on a kilowatt-hour basis, and at other times on the basis of peak load, or what might be termed a capacity basis. Without knowledge of load-factor, or simultaneous demand-factor, figures stated in these different ways may prove so misleading as to bring about expectations of returns varying all the way from $8 to $300 per horse power of station capacity. This confusion has played no small part in the mistakes which have been made; and these mistakes have caused the investing public to mistrust its ability to make correct deductions.

The problem of reliable service from long transmission lines is much further from solution than all of the other problems that have done so much to contribute obstacles to rapid development. Good engineering talent and other proper precautions will insure that the cost of construction shall be no greater than that promised. We can also accurately determine the available power, and can insure ourselves against disappointments in market. The best of engineering talent does not seem, however, able to promise for a transmission line the same continuity of operation that can be secured from a steam plant located at the point where the power is to be used, and this introduces many serious obstacles to the development of our water power projects. The importance of continuity of service varies in degree with almost every customer served. To some industries a mishap which causes even a fall in voltage or a change in frequency may be a serious matter.

MATTERS WORTHY OF DETAILED CONSIDERATION

In my observation and direct connection with water power propositions there have arisen many matters that deserve further thought and consideration by the engineers who are brought in contact with water power work, not only for their own benefit, but also for the education of the investing public and the power purchasing public. Some of these are as follows:

1. Methods to insure against interruptions or to lessen the harmful effect of interruptions.

2. Equipment to insure against interruptions or to lessen the harmful effect of interruptions.

3. Penalties for interruptions of service or insurance against interruptions.

4. Methods of charging.

5. Classes of service which can be advantageously supplied.
6. How to develop the market selected.
7. How to figure the amount of power it would pay to develop.
8. Calculations on depreciation.
9. Methods to determine the accuracy of engineers' estimates.

1. *Methods to insure against interruptions or to lessen the harmful effect of interruptions.* As previously stated, interruptions vary in seriousness with each class of consumers. To some even a long shutdown is relatively unimportant, while to others the slightest variation in frequency or voltage may prove highly objectionable.

With reliable reverse circuit-breakers, the tying in of several hydroelectric plants offers some insurance against interruptions.

If central-station companies are to be supplied, it might sometimes be commercially practicable, where the reachable market greatly exceeds the capacity of the plant, to run the transmission lines to several central stations, with the idea that no one of the stations will attempt to take more than a portion of its base load, and will always have some steam apparatus in operation, the capacity of which can be quickly increased to take care of any interruption of service from the hydroelectric plant.

In one case, arrangements were made several years ago to install a large steam turbine in connection with a relatively small water power plant, the generator of the steam turbine being designed to run as a motor while the vacuum on the turbine blades was maintained to reduce the windage loss, with the governor of the turbine so arranged that the slightest reduction in speed would cause the steam valves to open and the turbine immediately to pick up the load.

In a recent power negotiation, where the supply was to be furnished from two hydroelectric plants, it was suggested that one of these plants be run in the manner outlined above for the steam turbine; namely, that the generator should be run as a motor, and the water-wheel governor should be arranged to open up and drive the turbine if the speed fell off perceptibly.

In these cases the steam turbine, or water turbine, could be driven with a small amount of steam, or water, and the fields of the generator magnetized so that the load would be promptly picked up in case of interruption to service. This latter method, however, would be relatively less economical than to drive electrically, using steam or water only when service from the unit was demanded.

2. *Equipment to insure against interruptions or to lessen the harmful effect of interruptions.* It is customary on all important transmission lines to use either two circuits on the same pole-line or two circuits each on its own pole-line. The latter plan is far preferable.

Perhaps greatly added reliability could be secured by the use of extra conductors on each pole-line, with effective switching apparatus that would enable the extra conductor to be brought into use as quickly as possible.

The use of storage batteries is the first thing that occurs to one as a protection against interruptions, but their high investment cost and high cost of maintenance make them practically prohibitive when used purely to prevent interruptions of service.

Gas engines would be almost ideal, but the high investment charges make them practically impossible. They, however, have been adopted in one or more instances. A gas engine can be put into operation with marvelous rapidity, the time required being fixed by the time the electrical generator can be energized. Gas storage can be provided at a cost of approximately $50 per 1000 cu. ft., with no operating stand-by loss. This means an investment of about $400 per 1,000,000 B.t.u.'s for producer gas, about $80 per 1,000,000 B.t.u.'s for coal gas, and less than $70 per 1,000,000 B.t.u.'s for California oil gas.

Where producers are used, if the fires in the producers are maintained in proper condition, no storage capacity is needed; and perhaps no other similar class of apparatus can be run with such a small stand-by operating charge as a gas producer.

Unfortunately, however, a gas-engine power station represents such a high first cost that, in spite of the higher efficiency of the gas engine and the lower stand-by losses of the gas-generating apparatus, the commercial cost for purely relay service is higher than for steam equipment. If provision must be made for protection to service, a modern steam equipment offers about the lowest commercial cost.

This brings up several interesting points. The boilers chosen should be able to have their fires withdrawn without causing leaks, and boilers should be chosen having the least stand-by loss in relation to their maximum capacity. This means a boiler of either very high capacity or very low radiation and ventilation losses. Ordinarily we choose the boilers having the least consumption of fuel at full load, but for relay service we want the boiler having the least consumption of fuel at no load.

For wisdom in choice of boilers we need to know the efficiency from no load to maximum load, but the writer does not remember ever seeing an efficiency curve on boilers showing their economy from no load to full load. A slight increase in maximum capacity is of extreme importance for this class of work. It is unreasonable to suppose that with all the different makes of boilers now in use they all have anything like the same absolute capacity—and it is more than probable that the limit of capacity is determined by different features in different boilers. It is not likely that any very comprehensive determinations have ever been made on commercially economical, or ultimate, capacity of different types of boilers.

It is the writer's opinion that for this class of service the internally fired boiler deserves careful consideration, but perhaps only in a modified form. This boiler should show not only a small radiation loss, but ability to maintain tightness against unnecessary ventilation when run on bank, which is apt to be an important feature after the boilers have been in operation for some time.

This type of boiler, however, would be apt to be limited before other limiting features were reached by the lack of flue-gas conductivity of its fire tubes, which could be compensated for by a high draft pressure, but better compensated for by a modification in design.

If boilers are not to be run on bank, but are to be fired up if an interruption occurs, the methods to be used for quickly starting the boilers are of great importance.

The use of oil for fuel probably insures the greatest speed in starting up, but this fuel is often prohibitively expensive. It is, however, possible to use oil simply as an auxiliary in the starting of the boilers and then substitute coal, either hand-fired or machine-fired.

The writer does not remember ever having seen the suggestion made that powdered-coal firing be used for this class of work. Powdered fuel is almost the equivalent of oil or gas, and is ideal for the class of service under consideration. It probably costs more to powder fuel than to burn it, as received, with machine stoking; but for relay service, while the operating cost per ton of coal handled would be more, the investment charge would probably be far less; and a great gain would be made in the speed of starting as compared with ordinary coal fires, and a much greater economy of labor could be secured.

In the choice of steam engines the steam turbine would seem to be the only one worth consideration. The total first cost of steam turbines, including building, foundations, etc., should, alone, be enough to warrant their adoption; and if it were decided to turn these engines over idle, but with the fields of the generators magnetized, the steam consumption should prove materially less than for any other type.

3. *Penalties for interruptions of service or insurance against interruptions.* In a recent negotiation for the purchase and supply of power between a central-station company and a hydroelectric supply company, the question of continuity of service was given serious and detailed consideration. Various engineers were consulted and numerous suggestions were made.

The central-station company was not desirous of collecting any penalties, but insisted that they should have service of such degree of reliability that no serious damage should result, from such interruptions as might occur, to the business they then held, and that would enable the same rapid development of the business as then obtained to be continued.

It was concluded that any interruption, regardless of the length of such interruption, was harmful, and that the longer this interruption continued the more serious it became. It was also decided that one or more interruptions to the service immediately following the first interruption would prove more disastrous than if these interruptions were evenly distributed throughout the year.

As insurance against excessive interruption was being sought, and as the only insurance possible was that to be obtained through operation of the steam plant, it was decided that insurance should be obtained by running the steam plant (fully energized and ready to instantly take the load in case of interruption to the hydroelectric service) at such times and for such lengths of time at a stretch as might be necessary to insure against interruptions coming oftener than at certain intervals. For example, to take an extreme case of the simplest form, suppose it had been decided that no interruptions of any kind whatsoever were permissible more than twice in any twelve months. Then after any interruption the steam plant would be run for six months, ready to take the load at any time in case of failure of the hydroelectric supply. This would insure only two interruptions per year; for if another interruption occurred after the end of the six months, the steam plant would be run another six months, thus completing the year with only two interruptions.

It may seem curious, at first thought, to insure continuity of service, or, rather, to guard against more than a certain amount of interruption, by running the steam plant *after* an interruption. But, as interruptions cannot be foreseen, it is plain that the course outlined is the only one possible to accomplish the end aimed at with the least expense; that is. without running the steam plant continuously.

The above assumes that a steam plant is never subject to failure. But failures will occur at times in the most carefully operated steam plants, and this fact was taken into account by the allowance mentioned later.

The above also assumes that all interruptions, of whatever length, are equally disastrous, and that interruptions to all kinds of service, residence, business, and power, are equally disadvantageous. But as this is not the case, allowance was made for both the length of interruption and the damage to different kinds of service, as will be seen in what follows.

The load of the central station was divided arbitrarily into two classes, which we will call class *A* and class *B*. The power and the business district load together were considered as class *A* business, requiring the greater insurance against interruption. The residence load was considered as class *B* business.

The central-station company demanded that the length of time which the steam plant should be run after any given interruption should be fixed with reference to the duration of interruption and to the number of interruptions which had occurred during the year preceding and up to and including the interruption in question.

If the interruption in question was the first during said year, then the steam plant should be run of sufficient capacity to carry the class *A* load for 10 days for the first minute (or less) plus an additional day for each additional minute of duration of interruption; the time of running for each succeeding interruption to be compounded 20 per cent.

That is to say, for the

First	interruption	10	days	plus	1	day	per	additional	min.
Second	"	12	"	"	1.2	days	"	"	"
Third	"	14.4	"	"	1.44	"	"	"	"

et cetera.

And that at the same time sufficient additional capacity of the steam plant should be run to carry the class B load for 10 days for the first minute (or less) plus an additional day for each additional minute of duration of interruption; the time of running for each succeeding interruption to be compounded 10 per cent.

That is to say, for the

First	interruption	10	days plus	1	day	per additional min.
Second	"	11	" "	1.1	days	" " "
Third	"	12.1	" "	1.21	"	" " " "

et cetera.

In case an interruption should occur before the insurance feature had been entirely worked out on a previous interruption, then the remaining days of operation of the steam plant for the interruption previously experienced should be discarded and a fresh start made for another run of the steam plant, just as though the new interruption had occurred after, instead of during, a running period.

It was further provided that for the first two interruptions experienced in the 12-months period, the steam plant was to be run at the expense of the central-station company, on the assumption that two interruptions might occur even if the supply were from the steam plant alone. The expense of all subsequent operation of the steam plant was to be borne by the hydroelectric company.

Many other methods of penalties and insurance are in vogue, but as this plan is believed to be new it is submitted for discussion and for comparison with other methods already known to the members of the Institute.

4. *Methods of charging.* So many different methods of charging—or, perhaps, modifications of fundamental methods of charging—have been used that it is not surprising that even those skilled in the art are not familiar with all the deviations or the reasons for them.

The individual user cannot afford to pay more than the value of the service to him. The cost to him of supplying his own requirements will depend on (a), the maximum capacity he may demand, regardless of when this demand may occur, and (b), the total amount of current generated. His investment will be influenced by certain preparatory charges; and, generally speaking, the larger the capacity installed the less the cost on a unit basis of capacity.

While not always recognized, the cost of operation will be influenced, not only by the load-factor, but by the form of the load curve. Similar load-factors do not necessarily mean the same cost for current unless the shape of the load curve is the same.

The value to the user of the service from the hydroelectric company will depend upon what it will cost him to supply his own service; or, what service will cost him from some other source. The cost of service to the supplying company will depend, primarily, on the maximum capacity demanded by each consumer at the time of the maximum simultaneous peak on the station and transmission lines, and, in addition to this, the amount of current generated.

Where the customer supplies himself, he generally does so by the use of steam equipment. The larger items of his expense are those occasioned by the amount of current generated; the lesser items of expense are his fixed charges—which would come under the general term of "investment charges".

While the value to the user of the service of the hydroelectric company as compared to his own source of supply depends largely upon his absolute peak, the cost to the supplying company depends primarily on the demand of this consumer at the time of the hydroelectric company's simultaneous peak. Non-coincidence of maximum demands is, however, a legitimate source of profit to any supplying company; and this non-coincidence of maximum demands is generally a primary source of profit to the supplying company.

In each case, however, the value of the service to the consumer and the cost of the service to the producer depends primarily on the capacity demanded and the amount of current used. This is assuming that we are dealing with relatively large consumers.

In central-station practice large numbers of consumers are eventually developed having so small a current consumption and maximum demand that what might be termed the "consumer charge"—if it can be designated by this name without further explanation—assumes so much greater importance that it cannot be neglected. In fact, the condition has been reached where a large group of our central-station consumers requires a greater investment and maintenance expenditure for meters alone than is required for the generating equipment necessary to supply them.

It is unfortunate that it is not better understood that there is more than one factor which goes to make up the cost of electric service. Talking of power in terms of charges per unit of demand only, or in terms of kilowatt-hours only, has led to much confusion and many costly blunders. If capacity and current were not jumbled together, and if the value and cost of each were better understood, it would do much to contribute to further development of electric service sales.

The capacity cost to supply many consumers is far greater to the hydroelectric company than would this same cost be if the consumer supplied himself. On the other hand, the cost for current to the hydroelectric company is generally very small compared with the cost to the consumer were he to supply himself.

The capacity the consumer should pay for should generally be based upon his absolute maximum peak experienced at any period throughout the year. Any other method of arriving at the capacity charge is apt to lead to great inequities.

5. *Classes of service which can be advantageously supplied.* In the previous sub-heading attention has been called to the fact that there is more than one factor in the cost or value of electric service supply, and that the factor of capacity is apt to cost the hydroelectric company more than it costs the consumer.

If we were to assume that the maximum demands of all consumers occur simultaneously, then it is apparent that a point is apt to be reached where the total cost of service for any consumer is greater to the hydroelectric company than would be the cost of service to the individual consumer were he to supply himself; because if the capacity cost is greater there may not be enough current sold at the price charged to overcome the higher cost for capacity. Many consumers could therefore supply from their own plants all, or a portion, of their demand, over and above their average demand, at a cost to themselves less than to the hydroelectric company.

To illustrate more specifically, and preferably expressing values in mere arbitrary units instead of in dollars and cents: The cost of service from an individual steam plant might be represented by 100,000 units per kilowatt of capacity plus 100 units for each kilowatt-hour, while the cost of service from a hydroelectric company might be as much as 400,000 units per kilowatt of capacity plus 10 units per kilowatt-hour, being a relation in the first case as 1 is to 1,000 and in the second case as 1 is to 40,000. In spite of this great discrepancy in the relation between the fixed and output factors in the two cases, there is, nevertheless, the same cost of service at approximately 38 per cent load-factor. With a load-factor of less than 38 per cent the cost of service from the steam plant is the lesser, and at more than 38 per cent load-factor the cost of service from the hydroelectric plant is the lesser.

By securing a number of consumers of a diversified character, even though more transmission lines are necessary, a good load-factor can often be secured in spite of the fact that the individual consumers may have poor load-factors. And by getting consumers to adapt their operations to the ability of the hydroelectric company to supply—that is to say, by using some form of what is now called " limited service "—this same end can be realized.

No general and complete rules can be laid down whereby the maximum load-factor can be secured to a hydroelectric company. Rational methods of charging, properly explained so they can be understood both by consumers and by prospective consumers, will do much to contribute to a good load-factor.

The future situation in the hydroelectric supply business will, however, eventually be that of the market greatly exceeding the supply, and the natural remedy will be the installation of steam plants by the hydroelectric companies to enable all possible available water to be used. Central-station steam-power plants have been made a success in competition with individual steam plants, and the success of steam plants in connection with hydroelectric plants should be even more pronounced.

6. *How to develop the market selected.* Many disappointments have been due to failure do develop the available market, or by tardy development of this market.

Few people seem to realize the costliness of tardy operations. A completed plant with an undeveloped load can create a deficit of expected earnings which will require many months of subsequent operation to wipe out.

If the writer were to attempt the development of many of the large prospective water power undertakings, the transmission lines would be completed at the earliest possible moment, regardless of when the hydraulic generating plant could be put in commission; and if steam plants could not be taken over from prospective consumers to give in the aggregate enough capacity to carry on the development of the load, a relatively small steam plant in connection with the initial development of the water power plant would be installed new, and would be added to as rapidly as required to insure a proper load when the hydroelectric generating station was placed in commission.

Delays in securing business are often due to the inability of industrial establishments to change over their equipment until a natural period of shutdown occurs; and failure to take advantage of one of these natural periods may defer the time of getting this business for a matter of many months, or perhaps years.

The financial inability or indisposition of industrial plants to equip themselves with drives often occasions a serious retardation in the development of the expected load, and many power companies would find it greatly to their advantage to have financed the expense for their customers to use electric power even though compelled to take long deferred payments and more or less risk.

7. *How to figure the amount of power it would pay to develop.* It is the writer's belief that eventually hydroelectric companies will develop and sell all of the power that can be generated economically. To do this, in the absence of extensive reservoir capacity, will necessitate a heat engine auxiliary plant to supplement the hydraulic plant during low-water periods. The writer has no suggestion to make for the various purely local conditions which often must be met; but if a complete economic development is ever at all likely, then the design of the plant should be of a character adapted to such ultimate development.

May be a word on what this maximum development will not be out of place. Let us assume a hydroelectric development having simply a dam from which the water immediately enters the turbines and is immediately discharged to the river below the dam without any expensive canals, flumes, etc. In this character of development, hydraulic apparatus can be installed for carrying the peak load at a very much lower cost per kilowatt of capacity than by the use of steam. Not only this, but in this character of development all inequalities of load should be taken care of in the hydraulic plant; and if it is necessary to run steam, the steam load should be run for such time, and at a uniform rate, as will secure the most economic generation of steam power.

Steam plants or steam units can be started up and shut down only at considerable expense, while water units can be started up and shut down at practically no expense.

In the character of development used above as an example, with a market which far exceeds the water supply, and where fuel is relatively high, the hydraulic capacity installed can be equal to the maximum four days' supply of the stream. That is to say, the operation of a water turbine for 100 hours per year will, in some cases, warrant its installation. Under present practice most of us are only developing the so-called secondary power, which can be secured for a period of 10, or at least 8, months.

8. *Calculations on depreciation.* The writer does not wish to appear as viewing the water power problem from a purely financial standpoint, but still it is the financial standpoint which determines whether a water power shall or shall not be developed.

If anybody will agree to furnish the money, there are plenty of men who will agree to furnish all of the other ingredients for developing complete water powers at a rate at least twenty times the present rate of development.

So, after all, it is the financial aspect of the problem which practically controls the entire situation; and matters which unfavorably influence the financial aspect are matters to which we can well afford to direct our attention.

The question of depreciation is one which has an important bearing. Practically all of the present assumptions for depreciation are too high. Figures applied to depreciation are used in a general sense without regard to what the plant consists of.

The character of construction will largely influence the rate of depreciation. It is manifest that a plant having 10 per cent of its investment in wooden poles and 20 per cent of its investment in a masonry dam will have a higher rate of depreciation than the plant which has only 2 per cent of its entire investment in wooden poles and over 50 per cent of its entire investment in a masonry dam. Each individual class of property should be given its own true rate of depreciation, if any depreciation at all is to be figured, or else the different parts of the plant having the same relative rate of depreciation must be grouped together in figuring what the total depreciation will be on the entire property.

9. *Methods to determine the accuracy of engineers' estimates.* The writer has but one point in mind to speak about under this heading, although the importance of this subject would warrant more extended consideration. Without anything new to offer,

the writer desires simply to lay stress upon the point of greatest value.

Omissions and miscalculations are natural things to expect, and are always apt to be present. Checking and rechecking plans by the same, or other, engineers may not disclose the omissions or errors, while complete independent reports by two or more separate engineering corps, and the comparison of these reports, will practically insure against all omission and all miscalculations, making it possible to do the development work for the cost anticipated with a realization of all the power and the expected market at the price predicted.

CONCLUSIONS

Now, what has already been said may be considered simply as a preface to that which is primarily in the mind of the writer. Owing to the great breadth of the subject, no effort has been made to go into great detail, or to offer numerous specific suggestions, but only to make such comments as would arouse sufficient interest in the broad subject to produce further specific work.

It is hoped that the discussion which this paper may provoke will bring out much of value to further the development and operation of hydroelectric plants and lead to effective future work along these lines. The problem is worthy of consideration from many different points of view. The whole public has been aroused by, and applauds, the movement to conserve our natural resources. Nothing can contribute more to this desired end than the speedy development of our water powers.

Lack of knowledge (or faith) on the part of engineers, investors, public officials, and power purchasers is the greatest factor of retardation. No other existing body can contribute as much to the betterment of present conditions as can this Institute.

Our individual engineers and our engineering organizations enjoy positions of great influence with the general public, and this influence offers splendid opportunities for shaping the opinions of those elements of the public necessary to the development of these projects.

The Institute can do valuable work:

1. By educating the public to the recognition of the value of hydroelectric securities.

2. By such consideration and discussion as will bring about a

proper attitude on the part of the public officials toward the development of our water powers.

3. By papers and discussion on the methods of planning and developing which will insure that existing streams will be developed so as to realize more nearly their maximum economic possibilities.

4. By papers and discussion on projects collateral to hydroelectric development, calling attention to and enumerating what these opportunities are and indicating how and where necessary additional information can be obtained.

5. By encouraging frank and open discussion of past errors and their cause. The whispered gossip of alleged errors and failures to realize expectations are generally hopelessly inaccurate and prompted more by professional jealousy than by the desire to impart knowledge.

6. By the consideration of methods and equipment to insure continuity of service and of penalties for and insurance against interruptions. Had time permitted, the writer would have compiled a list, as far as possible, of all causes for interruptions which have been experienced.

7. By educational work on methods of charging, rates of charging, and factors which go to make up the cost and value of service, coupled with the endeavor to standardize all terms of expression.

DISCUSSION ON "COMMENTS ON THE DEVELOPMENT AND OPERATION OF HYDROELECTRIC PLANTS." NEW YORK, DECEMBER 16, 1909.

President Stillwell: There is perhaps no other subject at the present time within the horizon of the electrical engineer which involves so many important questions, both technical and financial, as the question of hydroelectric development. As you all know, the Federal Government and various State Governments have under consideration various plans for limiting the appropriation of water powers by private individuals and corporations Every electrical engineer with whom I have talked upon the subject approves in principle the idea of allowing appropriation only under a franchise which limits the term of use by the corporation or individual receiving the appropriation, but there is a great difference of opinion as to means and methods. The prospectus of the promoter who, in setting forth the advantages of these proposed developments, has not failed to emphasize all of the financial possibilities, is responsible for a general misconception on the part of the public and on the part of some of our Government officials in regard to the financial returns of these water-power developments. In a conference only two weeks ago, a prominent official of the Federal Government who is giving attention to the subject remarked that he had examined the prospectuses of certain water-power projects recommended by banking firms, in which it is stated that profits of from 30 to 40 per cent were certain. On the other hand, if we look around we find a large number of the more important water-power developments which have been attempted in the last 5 years in the hands of receivers. Of course there are water powers, especially in the West where coal is expensive, that have made large returns in proportion to the investment; but on the average these enterprises which are directly essential to the successful prosecution of a real policy of conservation have not succeeded financially. True conservation, of course, demands the most prompt possible utilization of our water powers, consistent with due regard to the rights of the people as a whole in this property, which belongs to them, and which should be safeguarded in their interests; but whatever arrangement is adopted, it should be such as to attract and not repel capital, if we are going to utilize with the greatest possible promptness these solar engines and conserve our fuel supply, which, as we now use it for power purposes, is burned at an enormous sacrifice.

Henry G. Stott: I am going to try to confine my remarks to only one portion of the paper, and that is to the question of the use of a steam plant as a reserve, and what proportion that steam plant should be to get the most economical results. Usually all engineering questions are finally solved by compromise. There are very few cases in which we find that we can solve any engineering problem on theoretical principles, as financial or com-

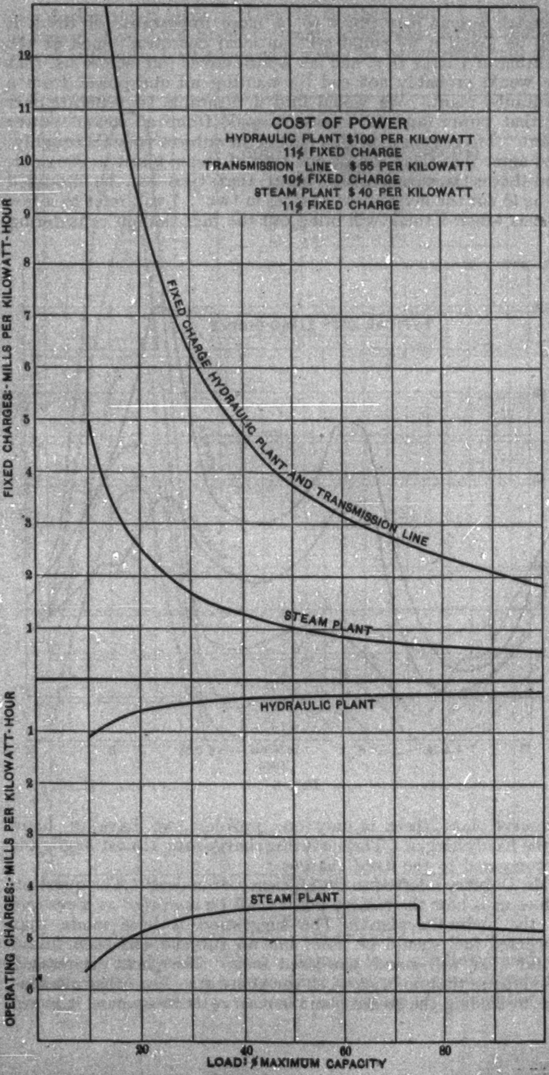
COST OF POWER
HYDRAULIC PLANT $100 PER KILOWATT
11% FIXED CHARGE
TRANSMISSION LINE $55 PER KILOWATT
10% FIXED CHARGE
STEAM PLANT $40 PER KILOWATT
11% FIXED CHARGE
FIXED CHARGE HYDRAULIC PLANT AND TRANSMISSION LINE
STEAM PLANT
HYDRAULIC PLANT
STEAM PLANT
FIXED CHARGES:- MILLS PER KILOWATT-HOUR
OPERATING CHARGES:- MILLS PER KILOWATT-HOUR
12
11
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
20
40
60
80
LOAD: % MAXIMUM CAPACITY

FIG. 1

mercial reasons may prove to be more important. I think it will be found if we could take an ideal condition, such as the lighting of a large city, and get a load curve put before us, that we would probably not end by wanting all our power from a hydraulic plant. We would find it desirable to generate part of that power (and for many reasons) from a steam power plant. I have gone over that part of the subject very thoroughly, and agree that there is only one type of steam plant to consider, and that is the steam-turbine plant; that type can be modified so as to cut the investment charges in two. I will refer to a few curves which I think will bring out the fact that in considering a reserve plant, there is only one problem we have in hand—the fixed charges. The operating charges are almost negligible as compared to the fixed charges.

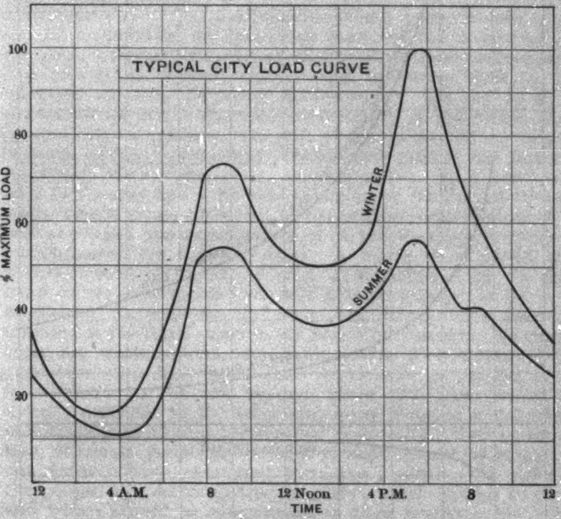

Fig. 2

Mr. Doherty referred to the efficiency of boilers. The question before us is how the reserve plant shall be operated as a reserve on the hydraulic plant? The suggestion is here made that powdered fuel should be used, but no furnace has been found so far that will stand powdered fuel. The heat generated is so intense that no brick work can stand it. The other alternative to holding the steam plant in reserve, is to operate it every day during peak loads. That is another point I will show in these curves. In order to bring something definite before you, I built up a load curve which may be representative of any

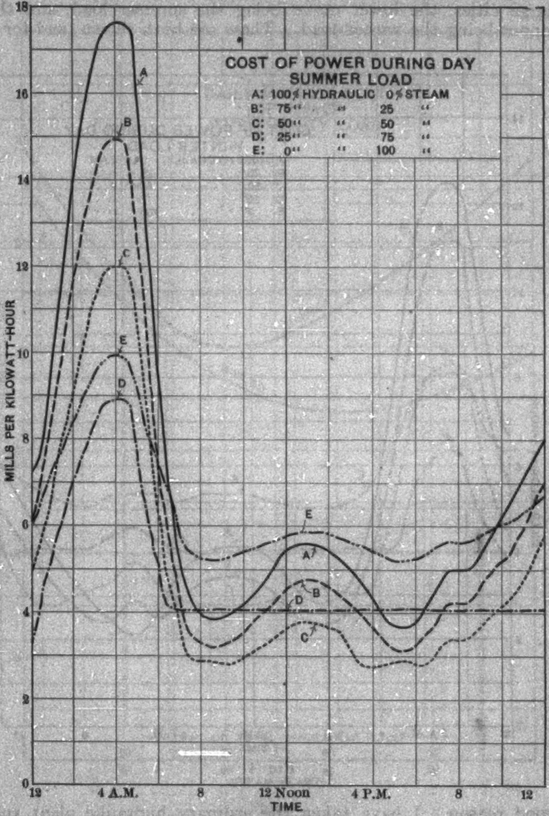

FIG. 3

large city: it is made up of a lighting load, a railroad load, and industrial-power load. In making these curves and calculations it has been necessary to make a number of assumptions. I cannot think in arbitrary units, as Mr. Doherty has done, so have used dollars and cents, and have therefore assumed certain costs.

Fig. 2 is a load curve which is typical of that obtained in our large cities, the lower curve being the summer load, and the upper being the winter load. These are both shown, and for a good reason. I have taken the ordinary hydraulic plant and assumed a cost of $100 per kilowatt, and $55 per kilowatt for a double transmission line of 100 miles. That makes a total investment per kilowatt of power delivered, including the step-up and step-down transformers, of $155. The total fixed charges are assumed to be 11 per cent on the plant and 10 per cent on

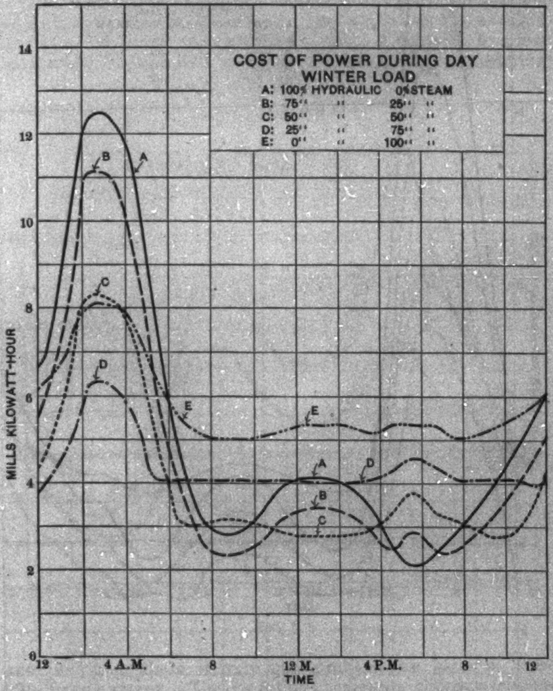

FIG. 4

the transmission line, annually. You will notice that the steam plant investment is $40 per kilowatt. That cost was arrived at in this way: a first-class steam-turbine plant will cost in the neighborhood of $80 per kilowatt. Supposing we order a 5,000-kw.

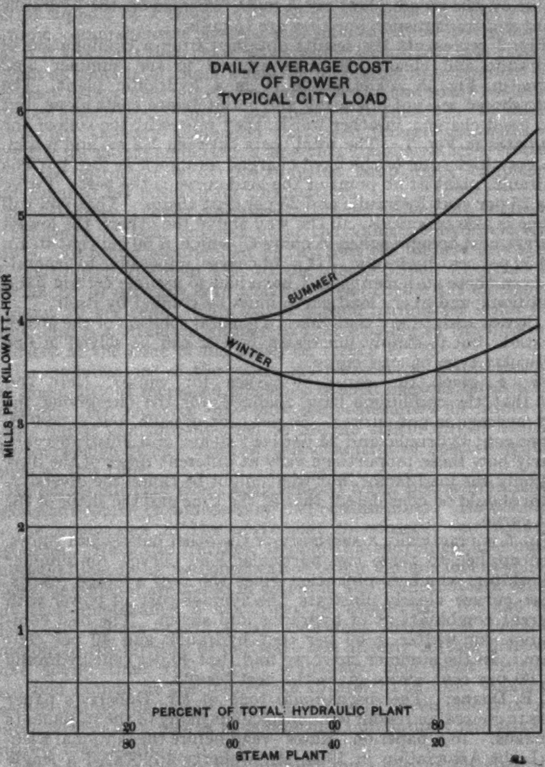

Fig. 5

unit, and stipulate that the generator shall have a rated capacity of 7,500 kw., and we also stipulate that there shall be a by-pass connection on the turbine, permitting high-pressure steam to be admitted to the second or third stages. This at once enables us to generate 100 per cent above the rating of the plant during peak loads, at a very small reduction of efficiency. The boilers should have a ratio of grate area to heating surface of 1 to 30, thus enabling us to drive them at 200 per cent of rating when necessary. The fixed charges at 10 per cent load-factor on the steam plant are 5 mills, whereas on the hydraulic plant and transmission line they are 15 mills.

Fig. 3 represents the results obtained from a combination of hydraulic and steam plants as applied to the summer load curve in Fig. 2. The curve *A* is a hydraulic plant. The costs shown are not operating and maintenance costs alone, but also fixed charges; in other words, they represent the sum of the ordinates in Fig. 1. The total costs between 1 a.m. and 6 a.m. are very high, due to the fixed charges, as shown in Fig. 1. The hydraulic plant at no point of the load curve is the best. Curve *B* is 75 per cent hydraulic and 25 per cent steam. That you will notice is also practically all the way above the others, the lowest average cost being reached in curve *C*, which is 50 per cent steam and 50 per cent hydraulic. It is, of course, impossible to generalize from these statements, as I have had to assume certain fixed conditions, and every load curve must be studied by itself.

I do not wish to say that this is a general solution of the power question but it simply illustrates how it can be solved in one particular type of load curve.

Fig. 4 gives the series of curves for winter. Here you find that the conditions have changed, for the one giving the best average is not curve *C*, 50 per cent of each, but is now *B*, 75 per cent hydraulic and 25 per cent steam, and illustrates very clearly how these proportions vary at different times of the day. Not only the load-factor, but what might be called the diversity-factor should be considered; that is, the time and the shape of the load curve.

Fig. 5 is practically a summary of the other curves and shows, when applied to these two particular load curves for summer and winter, which combination gives the best average results. These curves clearly illustrate the average cost of power with different combinations of hydraulic and steam. The best combination for winter is 60 per cent hydraulic and 40 per cent steam. In the summer curve we find that 40 per cent hydraulic and 60 per cent steam gives the best results.

S. E. Doane: The discussional tone of Mr. Doherty's paper tends to conceal or render less conspicuous many of the statements he makes. In a paper on "Rates" read before the National Electric Light Association in 1900, Mr. Doherty advocated a single service charge made up of two charges for two classes of service, as well as another charge for each kilowatt-hour. The purpose sought was to make the cost to the consumer depend upon the cost of supplying such consumer.

To his advice I think we will now universally agree, although there is some discussion as to whether the embodiment of this theory in the particular system he described is one which will be universally adopted, if any one system can be universally adopted. We should remember that Mr. Doherty's paper particularly disclaimed any advocacy of any universal system of rates, but that he did advocate the universal application of a principle. Recalling the discussion occurring at that time, it seems to me it was very largely overlooked that the paper really was in support of a theory and the embodiment of the theory in some comprehensive system was advocated on the ground that if it was right then there was nothing to lose and everything to gain at some later time, when the inevitable improvement in efficiency of incandescent electric lamps would find many systems of rates insufficient to meet the changed conditions. In other words, Mr. Doherty advocated that even though the weather were fair we should embark in a ship that could weather a storm. Since the introduction of the tungsten lamp many engineers have recalled his position on this matter.

Mr. Doherty speaks specifically of the effect of increase in efficiency of heat engines upon the value of hydroelectric plants. In round numbers let us say that the highest practical efficiency from the coal pile to the steam-driven fly-wheel is now about 10 per cent, and that for a gas engine the efficiency is about 20 per cent. This leaves a wide margin for improvement, and is a situation similar to that existing in the lighting industry at the time of his paper on rates.

His qualifications of the value of hydroelectric plants due to the possibility of increased efficiency of heat engines is most interesting. Mr. Doherty may only see possibilities for improvement, but it is a fair question to inquire specifically if he has any knowledge of any work of this character of special significance at this time.

He points out that every undeveloped water power represents a constant source of unnecessary fuel consumption. He testifies to the importance of the movement to conserve our natural resources. He states, further, that in this movement the most important feature is the conservation of our various fuel supplies. These statements are made in a simple and commonplace style, but their importance is worth serious attention. We can replant our forests—there is an enormous margin of increase possible to the fertility of our soil—but already certain districts have found their fuel supply exhausted and other districts face fuel famine in the immediate future. The mild language used in stating the importance of the speedy development of our water powers as a means of conserving our natural resources is entirely inadequate.

I do not pretend to see this problem more adequately than the author of this paper, but I regret that he did not confine his whole paper to this single subject. There is much of value and importance in this paper under other subjects, but there is no discrimination between the knowledge imparted which is of great importance and that which is of only minor importance.

Had the author cared to, he could have pointed out that nitrogen is the important element in maintaining the fertility of the soil, and that at present we largely depend upon our coal to supply this nitrogen. The coal burned under our boilers yields no nitrogen for fertilization, while the coal distilled for gas-making, and the coal carbonized for coke in modern ovens, yields appreciable amounts of nitrogen in the form of ammonia. So the fuel saved by the development of water powers means not only a direct fuel-saving but also the conservation of the material from which fertilizer may be produced. Few people to-day look upon our coal beds as immense deposits of fertilizer. Aside from our beds of natural fertilizing material, we depend almost entirely upon the nitrogen of our coals. Another method of nitrogenous production in form for fertilization is by means of electricity. The known processes for the fixation of nitrogen for the purpose of fertilization depend upon a production of power at a cost far below that price realized by the use of heat engines. This means the utilization of cheap water powers.

The products now used are either difficult of transportation or are bulky and mean much weight and much expense for freight transportation. The author has already pointed out that electricity may be transported to other localities at a lesser investment cost and with greater economy for irrigation purposes than for any other purpose. He might have pointed out that power could be generated at one point and transmitted to a point many miles distant for the creation of fertilization products at their point of application, thus necessitating the transportation of only one element of the product necessary for fertilization—transporting this by means of electric energy at a much less cost than matter which is acted upon by gravity can be transported by the usual means.

Mr. Doherty speaks of the failure to realize the predictions made by the investigating engineers in construction of hydroelectric properties and a reader might be led to believe that the investigating engineer is entirely to blame. This is certainly not always the case. Many of these disappointments have been due to mismanagement and tardy action on the part of others. The investigating engineer can only say what can be done, assuming reasonably competent management in every branch of the undertaking. In permitting his readers to believe that the investigating engineer is solely to blame, Mr. Doherty has in this one instance done a grave injustice to his erstwhile professional associates. I venture to maintain that even with the same investigating engineers, and no difference in the original report, few of these disappointments would have been realized had the execution of the entire enterprise been in the hands of any experienced and competent organization. Without wish to shirk responsibility, it is the duty of the engineer to place the blame where it belongs. It is an easy matter, but often unfair, to place the blame upon the investigating engineer. Were I doing this class of work, I should qualify my report by saying that I was unwilling to take the responsibility for the results promised, unless the financial, legal, organization, construction, contracting, and operation work were placed—if possible without divided authority—in the hands of people considered competent by me.

Strained financial ability, inexperienced direction, inharmonious relations between the various financial interests, unreliable contractors, incompetent construction superintendence, ignorant management of market development, ill-considered changes from original plans, and incomplete operation of the plant after completion—all have played an important part in the disappointments which have been realized. How unjust it is to blame the investigating engineer for the incompetency of every element which enters into the various divisions which go to make up the sum of the successful going plant, starting with simply a prospective stream development!

Financial means sufficient to control a corporation does not insure competency in any of these numerous branches. Mr. Doherty can well say that the proper investigation of a water power proposition is an expensive matter; and he might have added that the ordinary promotion house is loathe to spend its own funds beyond the extent required for writing an attractive prospectus.

Mr. Doherty says that the less known about a prospective development the greater attractiveness can be given to the enterprise, and he further states that "we are apt to have the condition that only the poorer projects will be developed." I do not deny the correctness of this statement, but why speak of it wholly in the future tense? Is this not in a large measure the condition which has existed for at least the past three years?

If my remarks are seemingly a criticism of Mr. Doherty's statements, or his method of statement, it will be a matter of much regret to me. His statement of the relative increased valuations of quasi-public and other properties, in his presidential address before the Northwestern Electrical Association in 1899, his paper on "Rates" at the Chicago Convention of the National Electric Light Association, his extension and amplification of Thomson's Law for determining the selection of transformers, his work on the proper selection of lamp efficiencies, have all been stated in a manner which made little impression at the time, but appear of vast importance in looking back over the several intervening years. I venture the opinion that his paper on "Organization", read at the Chicago Convention of the National Electric Light Association in 1908, and this present paper, either for their contents or their results, will ten years from now seem of much greater importance than they do now.

Mr. Doherty speaks of the retardation of electrical development owing to the confusion of methods of charging for current and misunderstanding of terms. This point is of sufficient importance to be worth consideration, but it seems to me the importance of this matter is almost completely eclipsed by the bad effects resulting from the use of systems of charging which are both irrational and inequitable.

All electric energy supply companies are furnishing not simply energy but service as well. The expense to provide service to each consumer bears no universal relation to the energy furnished to each consumer. To charge purely upon the basis of the energy supplied, without regard to the service supplied, or vice versa, means inability completely to develop the profitable market, and results in unjust inequalities between consumers and an aggregate charge for electrical employment beyond that which would be necessary if a rational system of charging was used.

No one can successfully deny that even within the profession an unwarranted difference of opinion exists regarding rates. This, therefore, seems to me to be a proper subject for comprehensive treatment by this Institute. The reference to rates and methods of charging in Mr Doherty's paper makes this a suitable time to consider the advisability of appointing a committee to handle this subject in much the same way as the High-Tension Transmission Committee has handled its subject. It is difficult for me to refrain from entering upon a discussion of this subject, but the time is too limited to do more than urge its complete treatment at some future time.

Under the heading of "Methods to insure against interruptions or to lessen the harmful effects of interruptions" Mr. Doherty speaks of rotating a steam or water turbine at full speed by using the generator as a motor, with a governor which will operate by a drop in voltage or frequency, opening the steam or water valve and immediately placing the unit in service as a generator. The expense for this will be partly offset by the use that could be made of the generator under such conditions to regulate the power-factor of the system. So far as I know this has never been done. I am endeavoring to emphasize this suggestion so it will not be overlooked if it has merit.

Under the next heading there is much that seems to have deserved more extended treatment. The suggestion that we do not know as much about boilers as we should is probably true. More knowledge is needed regarding not only their efficiency from no load to maximum load but also the maintenance of this initial efficiency.

The suggestion regarding the ultimate capacity of boilers and the various features which fix the limit should not be allowed to drop without further discussion, either by the author or other members of extended experience in boiler work. I cannot concur in the belief that the Scotch type of boiler promises greatest economy for this work. It seems to me its relative large water-content would alone be a serious objection. My opposition on this point to the views expressed in the paper are prompted solely by a desire to bring out the reasons behind this statement.

The writer refers to the starting of boilers by the use of oil as an auxiliary to coal-firing. Natural gas is not infrequently used where natural gas and coal equipment are used somewhat indiscriminately for firing, but I did not know that natural gas or oil were ever installed deliberately for the purpose the author suggests. If this method is in use and is not a new suggestion it would have benefited many readers had some examples or some literature on the subject been cited. The suggested use of powdered coal is also valuable, but it is open to the same comment; namely, that additional information would have greatly benefited the readers of this paper. My present information prompts me to say that except for cement burning, powdered coal is rarely used, and while we have the author's statement that " it is ideal for the class of service under consideration " and are willing to accept his opinion, yet we would appreciate his opinion as to how to study the problem to determine whether we can adopt it.

The method of " insurance against interruptions " is certainly both ingenuous and novel. It would not be difficult for any reader to identify the inventor of this method. Whether this method is generally applicable or not I am not competent to say. It seems to me that the time of day or night when the interruption occurs is a factor that should be considered in fixing the time of running the steam plant to insure against future interruptions. I do not consider myself competent to add any information of value to this subject, but I do think that lack of knowledge on this point, and lack of knowledge regarding rates and the factors which go to make up the cost and value of service, has prevented many supply companies from selling their service and many prospective purchasers from availing themselves of a service advantageous to them. Simply the inability of the purchaser and seller to understand how to buy and sell has played an important part in the retardation of electrical development. Not only this, but it has probably been the foundation for unnecessary competition.

It seems to me that Mr. Doherty touches upon a fundamental reason for the slow development of a market which will apply not only to the case of hydroelectric plants, but more widely and with just as great force to all central station work. The public must be made to understand the value of cost of service as well as the value of the electrical energy. Illogical and unjust methods of charging have served greatly to retard the fullest and most complete utilization of the capital invested in central station securities. As Mr. Doherty says, the fault in this matter lies to some extent with the electrical fraternity itself which it seems has not yet fully realized the importance of this question, so vital to the commercial success of its efforts. The engineer may make the physical plant as perfect from the purely engineering standpoint as anything on this world of ours can be. With this task complete, however, his duty is not done. He must do all he can to enable the plant to be used to the greatest advantage, and in doing so must become commercial enough to apply his engineering principles to the construction of a rate system which must not only be equitable but which will allow the greatest opportunity for future healthful development. The engineers and commercial men must work together. Engineering dictates must be accepted by the commercial man as the basis of operation. He must build on a solid foundation, otherwise his commercial structure will probably be seriously injured by some future and perhaps unforeseen development.

Systematic and logical cost-keeping methods have served to demonstrate that there are some principles of rate-making which cannot be disputed. A few years ago the idea of embodying them in a rate system was scoffed at. Some stations, however, with sufficient faith in their convictions, have demonstrated the entire feasibility of such procedure with satisfaction to their customers and profit to themselves. The complicated nature of the cost of the production of electrical energy and the comparatively slow progress in its understanding, should be a challenge to the Institute to investigate and establish correct principles, thereby placing the entire matter of rates upon a sound and logical basis. I think that this Institute should be a forum for the consideration and solution of such problems. These comments are prompted by the belief that the importance of proper methods of paying for or insuring against interruptions of service, together with a better understanding of matters pertaining to the method and rate of charge and the value of service, are not properly recognized. It seems to me that the method of insurance proposed by Mr. Doherty would be very expensive; for this reason I should like to see specific figures of the cost of this method.

That the investment and maintenance cost for meters alone for large groups of central station consumers is greater than the investment and maintenance cost of the generating equipment needed for their supply is a startling but probably true statement. It illustrates the fact that we are furnishing an expensive service entirely aside from the energy supplied. This fact also seems to sustain the position taken by Mr. Doherty in his paper entitled "Equitable, Uniform and Competitive Rates", in which he maintained that a uniform charge to each customer in addition to the capacity and energy charge was essential if equity were to be maintained as between all consumers.

In illustrating the usual characteristic difference between the elements of the cost of supply for a steam plant in comparison with a hydroelectric plant, Mr. Doherty's method is, I think, a valuable addition to the proper understanding of the problem. Under usual conditions there will always be some certain load-factor where the total costs are equal.

Mr. Doherty speaks of the need of maximum development of a stream in relation to the conservation of our natural resources. He also speaks of the advisability of giving hydroelectric companies the right of condemnation. It is hard to see how the maximum development of a stream can be secured without the right of condemnation, although this right alone will not insure the result which is sought. It seems to me that Mr. Doherty's position regarding the right of condemnation must be conceded by all as correct.

This brings us to the question of "how can maximum stream development be assured, even given the right of condemnation." It is an easy matter to see how hasty or unintelligent planning may bring about developments at the wrong locations, or of a character that will permanently limit the power yielded by the stream to a small fraction of the total power available.

It is also easy to see how inadequacy of funds may necessitate a 30-ft. development at the wrong location while a 100-ft. development was possible at the right location. It is also easy to see how this inadequacy of funds may forbid the purchase of land for reservoirs which would enable the flood waters to be stored and used for power purposes. I have no adequate solution to offer to this problem, and can only make one minor suggestion. It occurs to me, however, that by restating this problem it would perhaps insure not only greater interest in the solution of the problem but would also call the attention of a greater number of people to the problem. The obvious suggestion is that complete surveys of every stream capable of yielding power be undertaken by the Federal or State Governments, and that these surveys be directed to determining the nature of the development necessary to secure the maximum power from each stream. Since many states have spent large sums of money in their geological surveys, to locate coal, clay, cement rock, and other natural resources, it does not seem unreasonable for these same states to investigate their streams as a means of conserving their natural resources.

There remains now but one more point; namely, the maximum hydraulic development which commercial economy will warrant. When Mr. Doherty says that this development can be increased until the available water will permit some of the generating units to be used but four days in the year, it cannot be designated as other than a startling statement. It is so contrary to general methods now in vogue that it should not be allowed to stand without discussion as to its accuracy. Mr. Doherty gives an example in which the cost for steam power is cheaper for any load-factor less than 38 per cent, and then he says that "the operation of a water turbine for 100 hours per year will, in some cases, warrant its installation". It will be noted that 100 hours would represent a load-factor of only 1.14 per cent while the example given represents a use of equipment for 3328 hours, or 33 times as long.

I do not assume that the author of the paper is in error, in fact I believe he is right, but I do think that these two statements will seem contradictory or confusing to some of his readers unless further explanation is made. No doubt Mr. Doherty has long ago formulated some law for the determination of the maximum power which can be developed with commercial economy, and the statement of this law by him would add much to the value of the information contained in his paper.

I wish to give a word of explanation regarding my reason for presenting such a lengthy discussion. It is simply this—a paper merely presented before an engineering society is very often read in a cursory manner without the careful study it deserves. If the discussion serves to bring out various views upon the important principles involved it not only makes us think more carefully about what the author has said but it shows us new ways of looking at a subject that may at least be interesting.

Those of us who are interested in central station work have learned that what Mr. Doherty says, or writes deserves careful study, and I hope that by touching upon the points in his paper which seem of the most importance to me I may have helped to concentrate the interest of the reader upon them and perhaps caused thereby a second and more careful reading of the original article.

Cary T. Hutchinson: Mr. Doherty's paper offers a number of opportunities for comment, among them the matter of depreciation of hydroelectric plants. This is probably one of the most important matters touched on, and there is comparatively little regarding it in the literature of engineering.

Much data have been made public recently concerning depreciation of steam generating plants by the various public authorities, particularly the public service and railroad commissions, and the testimony of well known engineers is accessible. There seems to be a general consensus of opinion that the depreciation from " wear and tear " of a steam electric generating plant will vary from 5 to 7.5 per cent, and that in addition to this there is an entirely independent depreciation due to " obsolescence "; this also is put at from 5 to 7.5 per cent.

The heavy depreciation on such plants is due to the fact that all the machinery used is subject to very great wear and tear, and further that the type of steam generating plants changes rapidly. One has to go back only a few years to recall the gradual progression from small high- and low-speed engines belted to generators, to high- and low-speed engines direct connected; then to the marine type of engine, either compound, triple, or quadruple expansion direct-connected to generators —finishing with the most advanced type of reciprocating engines, as seen for instance in the Interborough plant in New York. But we all know that this type of plant is now considered in great part obsolete, and that new plants are building almost exclusively with steam-turbines in very large units, such as shown by the new Waterside plant in New York and the Quarry Street plant in Chicago. It is probably safe to say that the average life of any type of steam generating apparatus has been less than 10 years, although of course many plants have been in operation for a longer period of time. New York affords an excellent instance of obsolescence; it was only 25 years ago that the old Pearl Street Station of the Edison Company began operation. Since then that company has built and abandoned at least four distinct types of station, and would probably now consider as obsolescent the Waterside No. 1 completed only eight years ago.

Nor is there much reason to think that the end of this period of change has been reached. There is in sight the development of the internal combustion engine, the possibility of gas-turbines, and, for all we can say, of other means of converting the energy of coal into mechanical energy, which at present have not even been suggested. The fundamental reason for this is found in the very low efficiency of the process of converting the heat energy of coal into mechanical energy, 12 per cent being about the best figure for steam plants and, say, 25 per cent for gas-engine plants. There is obviously a wide margin between these figures and the best that may be imagined, and on this account a liberal allowance must always be made for depreciation due to obsolescence of plants of this kind.

With a modern hydroelectric generating station the matter is quite different: first, because the kind of construction is much less subject to depreciation through wear and tear; secondly, because the efficiency of conversion is much higher, and therefore there is not the wide margin for improvements. The efficiency of conversion in a modern hydroelectric plant from the theoretical energy of the water to the output at the bus-bars of the power house will be about 75 per cent, leaving a theoretical margin of only 25 per cent for all improvements. The efficiency of large electric generators and transformers is so high that there is no reason ever to expect material improvement in this direction; probably the cost of such betterment would exceed the advantages to be derived. There remains only the efficiency of the water wheels, and although this will undoubtedly be increased from the conventional figure of 80 per cent to 90 per cent, possibly this improvement would result in an increased output of only about 10 per cent, whereas with the steam plant the theoretical improvement may be put at from 200 per cent to 500 per cent.

The history of existing water power plants, as at Lowell, Lawrence, and other places, shows that they have a good long life; they are relatively stable in comparison with steam plants. These facts and consideration of the character of the machinery leads to the conclusion that depreciation due to "obsolescence" in a modern hydroelectric plant will be small.

An analysis of the depreciation of such a plant is given in Tables I and II. Table I covers the cost of construction of a modern, medium head, hydroelectric plant of large capacity, delivering energy at comparatively short distances in large blocks. While this table does not pretend to be exact for any one plant, yet I believe it to be fairly typical of construction of this character. It of course does not apply to the high-head plants in the West with flumes or ditches or steel pipe lines.

TABLE I

Cost of modern medium head hydroelectric generating and transmission plant		
Item		Proportional cost
1. Riparian rights for dam and flowage basin, real estate, franchises, organization expenses, preliminary legal expenses, cost of financing, removal of railroads, highways, bridges, and all expenses preliminary to actual construction work		20
2. Permanent construction, dam, power house, and waterways, etc.		30
3. Equipment of power house		14
4. Transmission system		13
a. Right-of-way	4.50	
b. Copper	1.50	
c. All else	7.00	
Sum		77
5. General expense, engineering, administration, legal, etc.		11
6. Interest during construction		12
Total		100

Item I of Table I covers the many costs that must be met, exclusive of the actual construction costs. Item 2 is principally made up of rock excavation and concrete. Item 3 is for the usual equipment, comprising water wheels, generators, switchboard apparatus, transformers, and the various small parts of the power-house equipment. Item 4 covers the transmission system, including sub-stations. Items 5 and 6 are self-explanatory. Of these items only 2, 3, and 4, comprising in all 57 per cent of the total, are subject to depreciation; and of these the greater portion of Item 2 is not subject to depreciation, as it covers rock excavation and concrete almost entirely.

Table II gives an estimate of the depreciation of the plant based on the cost given in Table I.

TABLE II

Depreciation of system			
Items of Table I	Proportional cost	Assumed life	Annual amount for depreciation, in per cent of total cost
1	20%		—
2	30	50	0.168
3	14	20	0.458
4	13	20	0.415
5	11	—	—
6	12	—	—
			1.041%
Equivalent to an average life of about 39 years.			

This table is calculated on the basis of the assumed life given for the different parts of the plant, the annual charges being compounded at the rate of 4.5 per cent.

Table III shows in detail the proportional parts of the total cost of the various elements going to make up Items 3 of Table I, and the life assumed for the different parts, together with the annual depreciation. This gives the total annual depreciation charge of 3.4 per cent, making the equivalent life of the power house as a whole 19 years; in Table II this is taken at 20 years.

TABLE III

Depreciation of equipment of power house

Item	Proportional cost	Life years	Annual amount for depreciation in per cent of total cost
1. Stop logs, gates, and other wood exposed to air and water..........	0.80	5	0.146
2. Flooring, roofing and hardware, and miscellaneous fixtures...........	9.80	15	0.472
3. Tile wainscoting, sewage, plumbing system, and metal window frames, etc..........................	2.45	15	0.118
4. Electric light and telephone........	0.80	10	0.065
5. Switchboard equipment...........	4.35	10	0.355
6. Cables and heavy wiring...........	3.90	10	0.318
7. Cranes..........................	1.25	15	0.060
8. Water wheels......................	33.75	25	0.757
9. Water-wheel governors............	2.90	10	0.235
10. Generators and transformers.......	40.00	25	0.898
	100.00		3.423

3.423%—Equivalent to average life of 19 years

Tables IV and V show similarly the details of the cost of the transmission line, and of the sub-stations which taken together make up Item 4 of Table I. The equivalent life of the transmission line is 26 years and of the sub-station 20 years. In Table II both are taken at 20 years.

The reason for the low depreciation on the transmission line is the comparatively high cost of the right-of-way, 45 per cent of the total. This together with nearly 25 per cent for copper makes the depreciation on the whole system low. The total depreciation due to wear and tear on a hydroelectric system of this character may then be placed at approximately 1 per cent, equivalent as a whole to a life of about 39 years, approximately the life of the bonds usually issued for the construction of plants of this character.

TABLE IV

Depreciation ot transmission line

Item	Proportional Cost	Life years	Annual Amount for depreciation in per cent of total cost
1. Right of way	45.	—	—
2. Towers	18.4	15	0.885
3. Special structures	5.1	10	0.415
4. Insulators	2.1	10	0.170
5. Copper	23.7	25	0.530
6. Installation	5.7	—	—
	100.0		2.000

Equivalent to about 26 years life

TABLE V

Depreciation of sub-station

Item	Proportional cost	Life years	Annual amount for depreciation in per cent of total cost
1. Land	6.0	—	—
2. Buildings	30.	25	0.67
3. Transformers	40	20	1.28
4. Switches, etc	16	10	1.29
5. Installation	8.	—	—
	100.		3.24

Equivalent to 20 years

It is difficult to see why in plants of this character there should be any charge for obsolescence; once in operation there is no sufficient inducement to change the principal features of its construction; in fact, these features cannot well be changed, as they are fixed in the original design. It is understood that switching apparatus may change, transformers, may change to some extent, and the minor appliances change, but the depreciation charge for wear and tear should cover all these features. The water wheels can only become antiquated by the introduction of something very much better, and the possibilities are not great. With these facts in mind, I believe that an additional depreciation charge of 1.5 per cent for obsolescence is certainly a very liberal estimate.

The fixed charges on the two classes of plants can then be taken somewhat approximately as given in Table VI.

TABLE VI

Fixed charges of steam and water-power generating plants

	Steam	Water
Interest	6.00%	6.00%
Insurance	0.50	——
Taxes	0.50	0.50
Depreciation	5.00	1.00
Obsolescence	5.00	1.50
	17.00%	9.00%

The total annual charge on a steam plant will be about 17 per cent, and on a water-power plant of the character under consideration about 9 per cent on the investment; if the investment were even approximately equal, the water-power plant would be able to deliver energy at a much lower price than the steam plant, but this is far from the case. A modern steam-turbine plant of large size can be built for $80 per kilowatt of rated turbine capacity. There are very few hydroelectric plants that have cost as little as $150 per kilowatt of rated capacity; generally the cost will run up from $200 to $300 per kilowatt of power delivered at the sub-station bus-bars, including all costs of the generating and transmitting system. For the purpose of determining the relative cost of energy supply by the two systems, $200 per kilowatt of delivered power will be a fair price for the hydroelectric plant, rather favorable than otherwise. The operating cost of the steam plant may be taken at say 0.5 cents per kilowatt-hour and of the hydroelectric plant at $2 per kilowatt per year of plant capacity, irrespective of output. The annual charge on the steam plant then becomes $13.60 per year and on the hydroelectric plant, including the operating cost, $20.00.

Table VII based on these figures then gives the cost of energy for the two plants for various annual load-factors; the cost for the hydroelectric plant is seen to be much lower, under all conditions of practical operation.

It is, however, ordinarily not the cost but the selling price of the energy from a hydroelectric plant that has to be considered. Ordinarily a hydroelectric plant is built to supply a market already supplied by steam plants, and the hydroelectric company is expected to sell to the steam company at a price less than the bare operating cost of the steam plant, the argument being that the operating company would have to carry fixed charges on its steam plant whether or not it is operating. The hydroelectric plant at the same time is expected to make a profit. Taking this profit at 6 per cent on the investment, or $12 per kilowatt of plant capacity, Table VIII shows the selling price the hydroelectric plant must obtain for various load-factors.

TABLE VII

Cost of energy per kilowatt-hour at various annual load-factors

Basis: $13.60 plus 0.5 cents for steam plant
$20 for water plant

Load-factor	Steam plant	Water plant	Ratio water to steam
15	1.54 cents	1.52 cents	100%
25	1.12 "	0.91 "	82
33	0.97 "	0.69 "	72
40	0.89 "	0.57 "	65
50	0.81 "	0.46 "	57
60	0.76 "	0.38 "	51
75	0.71 "	0.31 "	43

TABLE VIII

Selling price of energy from water plant with 6% on the investment or $12 per annum added to cost for profit

Load-factor	Selling price
15%	2.44 cents
25	1.46 "
33	1.10 "
40	0.92 "
50	0.73 "
60	0.61 "
75	0.49 "

If the steam company is willing to pay as much as 0.5 cents per kilowatt-hour, it is evident that the hydroelectric plant can supply only a very small proportion of the load of the steam company; that is to say, that portion of the load having a load-factor of 75 per cent. If the steam plant expects to get energy at less than its own cost, the hydroelectric plant cannot possibly sell to it.

This analysis shows clearly the preponderating part that the charges on capital bear to the total cost in a plant of this kind. Of the total revenue of $32.00 per kilowatt per annum, forming the basis of Table VIII, no less than $24, equal to 75 per cent, is a direct charge on the investment. If this plant were built as a part of the general system by a corporation which could get its money at 5 per cent, the total annual cost would be reduced to $18.00 per kilowatt per annum, and the selling price for energy at a 50 per cent load-factor would be 0.41 instead of 0.73 cents.

There are other important disadvantages that hydroelectric plants usually labor under; of these one of the most important is lack of flexibility. The rating of such plants is usually fixed by the output of the turbines at 80 per cent gate opening. This leaves just sufficient margin for governing and possibly sufficient spare capacity to operate at its rating in case of one unit being disabled. A steam-turbine plant will, on the other hand, carry very heavy loads in excess of its rating, the exact amount varying with the conditions; but its overload rating can be taken conservatively at 50 per cent for one hour. Hence, if costs are estimated on the basis of the one-hour capacity of the steam turbine plant they will be materially less than given in Table VII: for a 50 per cent load-factor, for instance, the cost per kilowatt-hour would become 0.58 cents instead of 0.81 cents, as given in the table; in other words, the cost would not be much greater than that of the hydroelectric plant.

That this point of view is correct is proved by several important contracts for the supply of steam energy recently executed, notably that of the Chicago Edison Company, with the Chicago Railways, in which the provisions for determining the maximum demand on which the charge of $15 per annum is based are such that no hydroelectric plant could possibly compete. The maximum demand in the case of a hydroelectric plant when selling to a big customer must be taken equal to the capacity of the machinery employed in supplying it, which is, practically speaking, the rated capacity. In other words, the maximum demand must be based on say the five-minute maximum, and little leeway can be allowed to the customer above the hard and fast maximum fixed by this consideration.

A further disadvantage that hydroelectric plants labor under, which leads to a high cost of the supply, is the necessity of ensuring continuity, against interruptions of the supply due both to the low-water period that exists on practically all the rivers in the country, and to the possible failure of transmission lines. As Mr. Doherty points out, the only certain way to ensure this continuity is the establishment of a steam plant at the point of consumption. This steam plant may be owned either by the customer or by the hydroelectric company, depending upon the contract arrangements that can be made for its use. But whatever these may be, it means an additional burden on the hydroelectric plant, which may amount to as much as $5 or $6 per kilowatt per annum in extreme cases, but which on the other hand may become as little as 0.75 cents to $1 per kilowatt if favorable arrangements can be made.

A consideration of these various elements indicates, I think, the reason why so many hydroelectric plants have been total failures from the point of view of a financial operation. In a word, they are so burdened with capital charges and costs that do not enter directly into the productive capacity of the plant, that competition with a modern steam plant is in many cases rendered impossible. The remedy would seem to be a total change in the methods of financing such propositions, by which they will be handled in the same way as the construction of a railroad or the establishment of a steel mill, or any other commercial enterprise.

H. W. Buck: Mr. Doherty has brought up one important matter, and that is the attitude of the Federal Government toward water-power development. I think that this Institute can do much toward educating the popular mind in this regard. There has been a great deal of literature circulated during the past year which has given false impressions about the fabulous value of water powers as they exist in nature. As a matter of fact, a mountain stream in the wilderness has practically no value whatever in itself. It is only when it is combined with a very large expenditure of money, ranging perhaps from $100 to $200 per horse power, together with the expenditure of a great deal of brain power in management, financing, and engineering, that this natural geographical situation, called a water power, derives a value. This value is contributed to only in a small degree by the water in its natural state. In this respect the people have a false idea about the value of those properties which the Government has lately refused to give over to private enterprise for development.

Furthermore, when a water power is developed and is successful, it is profitable only in a reasonable degree. At the present time active competition exists between water power and power from various forms of heat engine, and this condition is likely to continue for many years. Even good water powers cannot compete with power generated from steam at low load-factor in parts of the country where coal costs less than, say, $2.00 per ton. People have been led to believe that a water power is an absolute power monopoly, but such we all know is far from the fact. The Government also apparently assumes that water powers will, for all time, continue to be the only source of power. This hardly seems to be justified. The most efficient heat engine to-day has perhaps a commercial efficiency of 20 per cent, and there is therefore a large margin for possible improvement and economy in this form of engine. A slight improvement would still further increase competition with water power. Furthermore, the energy of water power is merely converted energy of the sum. It is quite possible that other means for the utilization of the sun's energy may develop in future generations. The attention of the Government is directed toward the preservation of water powers for the sake of posterity. It may be that when posterity arrives the energy of water powers will not be required at all, other sources of energy having superseded its use; and in the meantime the prevention of water power development represents a sacrifice for present generations and the loss of a great industrial opportunity.

The Government also seems to have adopted a discriminating attitude against water powers as distinguished from other natural resources. Economically there is no difference between a water power and any other form of natural resource. It is a situation in nature which can be developed for reasonable profit. So can timber lands, mines, farm lands, and all other property be developed and their potential value liberated for the benefit of mankind; but the agitation against the private development of water power as the one natural and injurious monopoly, without reference to all other forms of natural resources, seems to be a very one-sided form of socialism and an unjust discrimination against those who are interested in the development of water power.

This Institute can undoubtedly do a great deal toward correcting the wrong impressions which people have at the present time, with reference to the real situation respecting water powers and water-power development.

W. N. Ryerson: In speaking of collateral enterprises, Mr. Doherty says, rightly, that they should receive our careful attention. I have in mind one contract which provides that the customer is entitled to power generated by the water which would otherwise flow over the spillway of the hydroelectric plant. This contract is with an electrochemical company whose process enables them to reduce their consumption of power from time to time without serious interference; and the contract expressly provides that no interference shall take place with the continuous supply of power to other customers. Naturally, power is sold to this customer at a low rate, and a guaranteed minimum amount of power is provided, below which the customer cannot be asked to reduce his demand.

In saying

> Non-coincidence of maximum demands is, however, a legitimate source of profit to any supplying company, and this non-coincidence of maximum demands is generally a primary source of profit to the supplying company.

I take it Mr. Doherty does not mean that it is not legitimate for a supplying company to offer special rates for " off-peak " business, which I think every such company does.

The additional statement that,

> The capacity the consumer should pay for should generally be based upon this absolute maximum peak experienced at any period throughout the year.

Experience prompts me to say that I would prefer this should be based on the maximum peak during the term of his contract.

Mention has been made by various speakers of the subject of "Depreciation." In the state of Wisconsin there is a public service commission composed of able men, and not very long ago a certain town in the state, through its citizens, petitioned for a reduction in electric rates. The commission held hearings, and after finding that the company was not setting aside a depreciation fund, ordered it to raise its rates, in order that such a fund might be provided.

There is a recommendation in the paper that all terms of expression be standardized. I should like to see the term "load-factor" made more definite as to the time-interval covered by the maximum peak upon which it is determined.

Calvert Townley: I agree with the author of this paper that the Institute can perform a distinct service to the country at large by educating the public to a better understanding of the basic facts governing hydroelectric developments. Although my experience is limited, I can say that the more I operate and investigate water powers the greater respect I have for steam. It is unquestionably true that in New England there are comparatively few water powers than can be commercially considered for hydroelectric development, because they cannot compete with steam on the basis of cost. In the face of these facts, I am, naturally, reluctant to hear advocated the enactment of any laws by Federal or State governments which will put additional burdens on the present expense of developing or operating New England water powers. I believe that such development is of greater benefit to the communities supplied with power than it is to the capitalists who invest in the development itself, and that any additional burdens placed on such investment will tend to prevent all hydroelectric development wherever the margin of prospective profit is close, thus retarding by just that much the progress of any community which would have been served.

Compared with a steam-driven power station, a hydraulic plant is admittedly inferior in every particular except its cost of operation. Therefore, there must be a sufficient saving in such cost to warrant accepting other disabilities. The general public, and not a few engineers, seem to believe that because it does not consume fuel, water power costs nothing to produce. We seldom see the facts analyzed, but it may be interesting to inquire: what is the possible margin of saving in the total cost supplying power from water over the cost of performing similar service by steam?

Consider first the station itself. We see that it costs to operate a hydroelectric station about the same amount that it does to operate a modern steam-turbine station, omitting all boiler room expenses—fuel, boiler water, ash-handling, maintenance, and repairs. The largest of these items is of course fuel. At a New England seaport a high grade of anthracite coal would average to cost about $3.00 per long ton, and, therefore, a fuel consumption of minimum 2.5 lb. to maximum 3.5 lb. per kilowatt-hour results in the corresponding fuel cost per kilowatt-hour of minimum 0.334c. to maximum 0.466c.

To translate these figures into annual costs we must next consider the load-factor. If the yearly output of a station equal an average continuous load of 20 per cent of its rated generator capacity there will be 1752 kw-hr. annual output for each kilowatt of machinery installed. Similarly, an average output of 40 per cent produces 3504 kw-hr. annually for each kilowatt installed. Multiplying these two sets of figures together, we see that with the minimum coal consumption and the lower load-factor, the annual fuel cost per rated generator kilowatt installed will be $5.85. With the maximum assumed coal consumption and the higher load-factor, this cost becomes $16.32. I have taken the load-factors of 20 per cent and 40 per cent for the reason that these factors are not far from the limits found in hydroelectric developments in New England; that is to say, it is unlikely that a station will produce annually more than 40 per cent of the theoretical possible output, assuming every unit to be operated 24 hours a day, 365 days a year, at full rated load, while it is quite possible that under any but favorable conditions a 20 per cent output may be the best obtainable. These assumed conditions are, therefore, not theoretical, but practical. They must be reckoned with.

The other boiler-room expenses—mainly labor and repairs—may be partly, wholly, or more than wholly offset in a hydraulic station by the repairs to hydraulic structures, reservoirs, flume, forebay, tail-race, etc., and also by the cost of patrolling and repairs to the transmission line. The wide variation between hydraulic structures, and between the length, type, and voltage of transmission lines, makes impossible any concrete comparison of these cost items. We have to admit, however, that not infrequently in a hydraulic plant the items named will annually equal or exceed those of the corresponding steam station, leaving the net annual operating margin in favor of the water power no more than the saving in fuel.

The next item of cost, and one which many of us would like to forget when we wish to develop a hydraulic property, is the fixed charge. Here is the worst stumbling block. The average flow of New England streams is 40 per cent of their maximum flow, omitting freshets, while the minimum flow in years like the current year, and last year, may almost reach the vanishing point. The engineer who undertakes to develop a water power is, therefore, confronted at the outset with the question: What per cent of this maximum flow shall I develop? If the development be for the minimum flow only, the cost per unit of capacity may, become, and probably will become, so abnormally high as to be at once prohibitive. Per contra, if, in order to reduce the unit cost, a large percentage of the maximum flow be developed, it can all be used for but a part of each year, and a correspondingly large relay supplemental power must be provided. The usual decision is a compromise. Enough flow is developed to make the unit cost seem not too abnormal, and the disability of a shortage of water during, perhaps, two months of each year is accepted. During that time a relay steam plant must be operated. Many New England water powers cost to develop considerably more than would steam plants of equivalent rated capacities. In addition, transmission lines and relay steam plants of no inconsiderable size have to be paid for. It must not be forgotten, further, that whereas steam turbines are now commonly designed with large overload capacity, a water wheel has no overload capacity, and the rated capacity of a hydraulic development must, therefore, equal the peak load which it may be expected to carry. The ordinary commercial peak load is of such short duration that the overload capacity of a steam turbine is nearly as available as is the rated capacity; consequently the rated capacity of a steam plant may be from a quarter to a third less than that of the hydraulic station built to perform exactly the same service. The capacity and the cost of the hydraulic development must be further increased on account of the transmission losses, which reduces by just so much the power available at the point of utilization. Let me illustrate what I have said by applying some average conditions and working out a concrete case. Let us compare the total cost of producing current by water and by steam under the following conditions:

TABLE I

Hydraulic Development—5000 *kw. capacity*	
Cost of same, not including transmission lines	$125 per kw.
Duplicate pole lines for transmitting power to point of utilization	$50,000
Sub-stations at distributing points, capacity 4500 kw.; cost of sub-station	$8.00 per kw.
Peak load at power station	4000 kw.
Average load the year round on station—that is, 30 per cent load-factor.	1500 kw.
Average loss in line and sub-stations	10%
Minimum flow of water for two months	1000 kw.
Steam relay at distribution center, rated capacity with 50 per cent overload guarantee	2500 kw.
Cost of steam relay per kilowatt rated capacity	$100
Annual labor and material cost to operate the hydraulic power station, sub-station and to maintain the property	$25,000
Cost to operate steam relay plant and supply the insufficiency of power during two months, also to keep it on call for the remainder of the year	$3,000
Interest, depreciation, taxes, etc., on total cost of hydraulic plant	10%

From these assumptions we at once deduce the following figures:

TABLE II

Capital Invested.	
5000 kw. at $125	$625,000
Pole line	50,000
Sub-station, 4500 kw. at $8.00	36,000
Steam relay, 2500 kw. at $100	250,000
Total investment	$961,000
Fixed charges, 10 per cent	$96,100
Operating and maintenance cost of hydraulic plant	25,000
Operating and maintenance cost of the steam plant	3,000
Total annual cost	$124,100

Output 1500 kw-hr. 24 hours per day, 365 days = 13,140,000 kw.; less 10 per cent loss in transmission = 11,826,000 kw-hr. net power delivered at point of utilization, making the cost per kilowatt-hour delivered—10.5 mills.

Had this power been produced by a steam turbine plant located at the point of utilization we may assume the following conditions:

TABLE III

Capacity steam plant, to deliver a peak load of 4500 kw., corresponding to that required for the hydraulic plant, less transmission losses, the steam plant to have an overload capacity of 50 per cent; that is, 6000 kw., or if four 1000 kw. units be selected, the overload capacity with one unit out of service will be 4500 kw., equivalent to the peak load. Cost of steam plant rated capacity	$100 per kilowatt
Coal consumption	3 lb. per kilowatt-hour output
Cost of coal	$3.00 per long ton
Labor and maintenance charges same as for the hydraulic plant	$25,000 per year
Fixed charges and depreciation, capital invested as against 10 per cent for the hydraulic plant	12 per cent

On the basis of these assumptions we at once deduce the following figures:

TABLE IV

Investment necessary.	
4,000 kw. at $100	$400,000
Fixed charges at 12 per cent	48,000
11,826,000 kw-hr., fuel cost	47,304
Other operation and maintenance charges	25,000
Total operating and fixed charges for the year	$120,304

or a cost per kilowatt-hour produced of 10.1 mills, slightly under that of the corresponding hydraulic cost.

It is clear from these figures that, although the operating cost of the hydraulic plant is very much lower than that of the steam plant, its fixed charges are so much higher that the saving is more than offset. Therefore, if its construction can be justified, a reasonably low cost of a hydraulic plant must be assured beyond any reasonable doubt, or a high load-factor must be secured, or both.

On these two points there is a vast amount of current misinformation. Not a few hydraulic projects, some of them very large ones, have put their investors badly "in the hole" because the enthusiasm of their promoters had underestimated the cost of their construction, and overestimated, very much overestimated, the average load to be secured.

I am operating a 6000-kw. water power which is developed for only 60 per cent of the 10 months' stream-flow instead of 100 per cent, as in the example taken, and it should, therefore, have a greater per cent of minimum flow to draw upon. This power is further supplemented by three steam relay plants. We apply all of the power generated to our own service, and we have a heavy demand for it. We are, therefore, able to operate under favorable load-factor conditions. Notwithstanding this fact, the best average annual load-factor I have been able to obtain is 38 per cent. The figure of $125 per kilowatt for hydraulic development is under the average estimated cost of those New England powers that have come under my own observation. Many powers would materially exceed this cost. The steam plant cost of $100 per kilowatt is a fair average cost, as most of you know, although it can be frequently lowered, as also can the coal consumption of 3 lb. used in my example. These conditions, then, are practical, present conditions, with which we are confronted; and in the case of which I have spoken no one would consider the installation of the hydraulic plant, because in addition to costing more to produce this power the possibility of interruption by ice, freshets, damage to the reservoirs or other hydraulic structures, breakdown of pole line, etc., render the service less desirable, and, consequently, add an additional element of expense.

It is doubtless, true that the nation's visible coal supply is decreasing, and that the cost of that fuel may, therefore, be expected ultimately to advance. The predictions of such an advance, however, are not new. The same prediction has been repeated continually for several years, in the face of which prediction the cost of coal consumed in our plants per kilowatt-hour has continued to steadily decline. If, therefore, we invest in New England water powers, expecting that our profits are to come from the expected shortage of coal supply and the consequent higher comparative value of water power, we should first decide whether or not we wish to reap the benefit of that profit ourselves or allow posterity to do so.

I have limited my remarks to New England because I am more familiar with the conditions which are prevalent there. I have no desire to reflect by implication on any hydroelectric development past or prospective which any member of this Institute may have investigated and approved. But I wish to point out that the majority of men with whom I have talked regarding the general hydroelectric proposition seem to have in mind Niagara Falls, or some one of the few very large water powers in the country, and to bear but little in mind the very large number of moderate sized powers in our hundreds of streams. I have regarded this fact as unfortunate, and from information furnished to me I am led to believe that our governmental authorities have an entire misconception of the value and importance of water powers. If there is any prospect of the so-called gigantic water power trust that has been exploited more or less in the press, I believe our government should go slow in discouraging such an organization, not that I am in favor of trusts or monopolies, but because in the formation of any large syndicate competent advice and assistance is at once sought, and there is a much smaller chance of blundering in estimated cost of construction, operating expenses, fixed charges or receipts, with consequent inevitable financial disaster, and if the justifiable development of the really useful water powers of the country is retarded by arbitrary restricting laws, the country, not the investor, will suffer.

Julian C. Smith: I have only a few facts to bring before the members of the Institute, but before giving the results of several years' operation, I would like to indicate briefly the conditions of operation. We have a large power station, two separate pole lines about 100 miles long, a large receiving station, where almost all of the power, about 95 per cent, is taken. The pressure is 50,000 volts.

I have tabulated the results of seven years' operation of the Shawinigan system in two classifications: first, what might be termed a geographical one; the second deals chiefly with the causes of interruption. I have called an interruption of service, any actual interruption to the service delivered. As all of this service is delivered through synchronous motor sets, this classification includes many interruptions which might on other systems be classed merely as disturbances.

TABLE I

Transmission lines 27 per cent.
Lightning 21 per cent.
Sub-stations 11 per cent.
Power house 24 per cent.
Terminal stations 13 per cent.
Unknown 3 per cent.

TABLE II

Elements 8 per cent.
Interference 7 per cent.

Operators 20 per cent.
Lightning 21 per cent.
Breakdown of machinery 21 per cent.
Breakdown of insulators 11 per cent.
Bad construction 11 per cent.

The first table requires no explanation. The second, however, may be elucidated as follows:

By "Elements" I mean such interruptions of service as were caused by exceptional and extraordinary conditions—forest fires, hurricanes, floods far beyond the average, or ice movements of exceptional severity.

By "Interference" I mean interruptions caused by persons not employed by our company. This includes such causes as farmers blasting stumps near the lines, malicious interference, shooting at insulators, moving houses under the transmission line, etc.

By "Operators" I mean all those interruptions caused by the company's men, either through carelessness or ignorance.

By "Lightning" I mean the interruptions caused at the time of the storms—doubtless some of the interruptions under breakdown of insulators should be put under this classification. Under classification "Breakdown of machinery," I have put all interruptions caused by generator troubles, exciters, transformer burn-outs, switch failures, etc. Under "Breakdown of insulators" I have put all shutdowns caused, or apparently caused, by insulator troubles. This includes burned or broken pins, burned poles, and cross-arms. Under "Bad construction" I have tabulated the interruptions caused by the immediate failure in service of new apparatus or interruption caused to the operation by reason of construction in the neighborhood.

It will be observed from Table II that the three main causes of troubles are operators, lightning, and machinery.

The number of troubles caused by lightning and machinery is becoming less every year. By the use of better lightning arresters, protective relays, etc., the lightning disturbances are being reduced. By the more rigid testing of machinery, the making of trial runs, lasting some days, the use of much heavier and better oil switches, and the use of machinery better adapted for the purpose, the trouble from this cause is also being reduced.

The troubles caused by operators is a different story. There are two sorts of errors made by our men, one due to ignorance and the other to carelessness. We endeavor to give the men a thorough training and limit the number of men who actually handle the switching operations. There is a large personal element involved, however, as the operation of a large station calls for men who are content to perform monotonous duties for long periods of time, and yet find these same men keen, self-reliant, cool-headed and active in case of emergency. I wish that other members of the Institute who have had operating experience would state how they have met this problem.

Henry L. Doherty: Mr. Doane calls attention to the fact that our fuel beds were not only fuel beds, but immense beds of fertilization products. That subject was in my mind when I wrote the paper, but it was not included. Coal distilled in an ordinary gas-house retort will yield about 5 lb. of ammonia per ton of coal distilled; I say this in the absence of reliable data, but my recollection is that it requires the equivalent of about 30 lb. of ammonia to fertilize an acre of ground, in the form of ammonia sulphate. Such fertilization would provide double the average production of the wheat lands of the United States. I think it can safely be assumed if all of our coal were gassified in coke ovens or retorts, it would add at least $500,000,000 to the fertility of our soil. Considerably over one billion dollars would be added to our farm products if the bituminous coal now burned in our boilers was gassified by the Mond system and the resultant ammonia used for fertilization. From this it will be seen that enormous farm-product wealth lies in our fuel beds, if it can be made commercially available.

Mr. Doane, Dr. Hutchinson and Mr. Stott called attention to the feature which I attempted to bring out in my paper, that at 38 per cent load-factor the steam and the hydraulic plant can be operated at equal cost, below that the steam plant at lesser cost and above that the water-power plant at a lesser cost. Mr. Doane specifically brought out the point that I was seemingly contradicting myself when I stated that it was possible to install water turbines, even though they were only run 100 hours each year. It must be remembered that we cannot take our average investment cost for a hydroelectric company in figuring what we can do in the way of additional installation equipment, because the main preparation expense is often work on the river, perhaps producing no physical property, or which cannot be seen, like the blasting out of a channel or something of that sort. Then there are other preparation expenses, which are enormous. With the type of simple development mentioned, however namely, simply a dam across the river and the water flowing directly to the turbine, and flowing from the turbine to the river below, while the total cost for the water power and transmission lines might be as much as $400 per horse power, perhaps the additional cost of adding water-power units might not be over $35 per horse power. We would then have only to figure fixed charges on an additional $35 as the investment for each additional horse power, thus verifying Mr. Stott's curves, where the steam plant and hydraulic plant, by virtue of the lesser fixed charges, show higher economy on a low load-factor. An additional installation of water wheels for carrying the flood flow of the river works out in the same way. But these cannot be depended on to furnish capacity; they furnish current only, because there is not both water and capacity to keep them running all the time.

The country is influenced by the belief that an attempt is being made to control these water powers by a so-called trust.

I have no doubt that the public can be induced to abuse anything that they believe is going to result in trust control. That is an awful bugaboo to them. The same opinion exists regarding the so-called watering of stock. The public has been taught to believe that the capitalization beyond the actual cost of any property means the watering of stock. I do not see why the cost of a property need represent its capitalization. Let us assume there is a water power, possibly in the northern part of this state, and let us assume that we can buy the necessary land and riparian rights, etc., for $50,000. Let us assume further that we can take another $950,000, and complete a plant having a hydroelectric capacity of 10,000 kw. That means an investment of $1,000,000 of real money. We must take all the risks, and if it is not a success we are the losers. We would be very deficient in mental ability if we were willing to invest $1,000,000 in a plant which might be worth $1,000.000 and no more. We certainly would be foolish to put money into it unless we had the possibility of making the plant worth $2,000,000. If we believe it is going to be worth $2,000,000, and if we put our money in it, believing that it will be worth $2,000,000, we are not doing any one any injustice if we capitalize it at $2,000,000, provided there is no misrepresentation of the facts. If things are worth only what they cost, then that must end the revaluing of our real estate, because there is a remarkable example of a value away beyond the original cost. Assume that a plant which cost $1,000,000, had proved a failure, had proved its inability to earn interest on a single dollar; surely it could not be contended that that plant is worth $1,000,000, because it cost that much. In other words, the cost of a thing does not represent its real value.

Mr. Buck does good service in calling attention to the fact that the public have a well-developed case of hysterics—although he did not put it so strong as that—over water powers as one of our natural resources, and the growing fear that some one would develop these and reap a profit, while very little has been said about the other natural resources, all of which have proved equally, or even more profitable than water powers. That point was brought out by Mr. Townley, who remarked that the one to benefit primarily by the development of the water powers of the country is the public, and not the capitalist. The capitalist can find other places to put his money.

Mr. Martin says that an interruption of service, under the plan suggested in my paper, might produce a very long period of the operation of the steam plant. I did not attempt, purposely, to give full details as to the plan of insuring service. It was not intended that insurance should be required beyond the time necessary to put the steam plant in operation, which we would assume would be done under different conditions all the way from one half hour to two hours.

Mr. Stott stated powdered fuel could not be used in any type of furnace. I have had some experience in using powdered fuel and do not hesitate to say it can be applied to any class of service, although I agree with him that powdered fuel cannot be applied to ordinary furnace practice developed for producer gas, or other gases of much lower flame temperature, which contributes heat to the bounding surface.

Mr. Ryerson spoke of a contract that had been made for the utilization of waste water. As a favor to the other engineers who are interested in this class of work, Mr. Ryerson might contribute a written discussion telling us more about that contract. I have no doubt that such a contract would make money and make a slightly profitable water-power plant more profitable to its owners. Mr. Ryerson also spoke about special rates for off-peak business, and rather drew the inference, from my paper, that I held that non-coincidence of simultaneous peaks is a legitimate profit for the central station, and that they should charge the same, whether the consumers' peak occurs at the time of their simultaneous peak or not. I did not mean that inference to be drawn, although I think it is warranted. It is my opinion that the consumer should pay for what he would be compelled to furnish himself, but if the company sees fit to make any certain rate for the sake of getting business, which is extremely favorable to them, due to the fact that the peak occurs at some time when it is not a tax on them, they certainly should have the right to do so. I believe we should be allowed, even where we are strictly quasi-public corporations, to take any business that creates more revenue than its specific cost, on the assumption that it still leaves something as a contribution toward our overhead burden that will lessen the burden on other consumers. In other words, we should not be forced to figure against all business, whether the traffic can bear it or not, its proportion of the unavoidable overhead expense.

Mr. Ryerson also called attention to the point that the peak of the consumer should not be taken simply for the year, but for the term of the contract. In that respect I think Mr. Ryerson is right. We are not simply interested in that year, and if it is possible to do that we ought to put it on the basis, as nearly as possible, of what the consumer would have to do if he were to furnish his own plant, for there he must not only pay for the peak he uses, but he must anticipate, provide, and pay for the peak he expected before his actual demand was experienced.

Carl Schwartz (by letter): One of the best features of the paper presented is that it touches upon almost every problem in connection with hydroelectric development. There is one question particularly that seems to be in a rather unsettled condition—the amount and most economical kind of auxiliary power to insure against interruption and to improve the load factor.

If the first costs of a hydroelectric development are high, the fixed charges will frequently exceed those of small heat power plants of prospective consumers; taking their business then, usually means relying on the diversity-factor of the load and on an auxiliary power plant to carry the peaks. The investment for auxiliary power will depend for instance, among numerous other questions, on the cost of the hydroelectric development itself. If its cost per kilowatt is large, to be a paying investment it should allow operation with a high load-factor. On the other hand, the installation of auxiliary power increases the investment still more so. The question of auxiliary power capacity will always be a matter of detail calculation for each particular case.

The merits of steam or gas power, however, for auxiliary plants can generally be compared and the following comparison is submitted.

Taking the steam turbine station at, say, $90 per kilowatt, and the cost of coal at $3 per ton, we find that between 25 per cent and 30 per cent station load-factor fixed charges and running charges balance each other. If, therefore, the station load-factor is lower than, say, 25 per cent, the station should be built at low first cost. If higher, say 30 per cent, it will pay to install refinements that may slightly raise the first cost but improve the economy. The same reasoning applies to a gas-power plant, except that if we take the first cost at about $140, the fixed charges will overbalance the running charges until the load-factor exceeds 60 per cent.

It is thus clear that if a gas-power station were to be given preference over a steam-turbine station, the auxiliary power plant should operate under a good load-factor. As this is ordinarily not possible, the steam-turbine station should be the best type of auxiliary plant. Its lower first cost and high overload capacity compared with the gas plant makes it serviceable for low load-factors and allows the bulk of the load to be supplied from the water-power plant where the operating expense is an insignificant item. The design of such a steam turbine plant and its method of operation will depend on the conditions to be met; and there is no difficulty in making, if desired, the design most economical for a certain load-factor and intermittent operating conditions.

An ingenious plan for insurance against interruptions of service is outlined in the paper, but it supposes the use of a steam station of the full capacity of the hydroelectric plant. This must considerably increase the fixed charges and thus the costs of the service to consumers. This amount of insurance may be required, for instance, for light and power service for a city, but it would be prohibitive for purposes where only a low price of current can successfully compete against or replace other service or create new industries.

The financial standpoint is probably the most important feature to be considered, for the reason that all engineering calculations, whether they concern the amount of power advisable to develop, the methods to do it, whether duplicate lines or auxiliary power are advisable to install, etc., are based upon financial considerations. Inasmuch as in hydroelectric plants over 80 per cent of the cost of current is made up of fixed charges, it is easy to realize the importance of the correct valuation of depreciation. The depreciation period should not be too long, say not more than 15 years, because of possible changes in the art of engineering. For instance, the generation of current by heat is still very inefficient, and we may some day see great improvements which might affect in some cases the valuation of hydroelectric properties were the depreciation period too long.

C. P. Fowler (by letter):

THE VALUE OF WATER-POWER SECURITIES

1. *Labor.* Hydroelectric plants differ from other enterprises in that the number of wage-earning employes is comparatively few and of a highly intelligent kind, the probability of differences between employer and employe, and of strikes, are thereby minimized. Furthermore, freedom from difficulties of fuel supply incident to strikes on railroad and at coal mines, freight congestion, etc., tends to stability of earning power for this class of security.

2. *Raw material.* Large investments in raw material and fuel are unnecessary with hydroelectric plants as with industrial enterprises and steam plants.

3. *Depreciation.* The amount that is necessary to set aside annually to cover depreciation for hydroelectric plants is probably not more than from one-third to one-half of that necessary with an equivalent steam plant. This amount even bears a relatively smaller ratio to the depreciation rate of industrial plants where, in addition to the depreciation of machinery, a certain amount must be set aside to cover goods that have become unsalable.

4. *Operating expense.* Another feature, peculiar to hydroelectric plants is the possible large increase in gross earnings without a proportionate increase in operating expenses. To illustrate this point, I give below a tabulated statement of the ratio of operating expenses to gross earnings of a hydroelectric development of which I have knowledge, covering a period of five years of operation.

First year	53.5	per cent
Second year	32.4	"
Third year	30.0	"
Fourth year	23.0	"
Fifth year	23.0	"

During the five-year period referred to above, the gross earnings increased over four times while the operating expenses for the fifth year of the same interval were less than twice those of the first year of operation.

5. *General.* These conditions indicate the small demands made by hydroelectric plants for working capital compared with other undertakings. This is of great importance in times of financial stringency such as were experienced in 1907.

THE RELATION OF WATER-POWER DEVELOPMENT TO THE CONSERVATION OF OUR NATURAL RESOURCES

Mr. Doherty very properly points out the interrelation of water-power development and the conservation of our various sources of fuel supply. Our chief fuels are wood, oil, and coal. Wood fuel is now almost a thing of the past, oil although used extensively in some parts of the country is of limited supply, and before long may cease to be an important factor in the problem. Coal, therefore, is the chief remaining fuel; but when it is remembered that the increase in coal consumption in the United States has doubled during each decade—a greater rate than the increase in population—the necessity for prompt measures to reduce the drain upon our coal deposits at once becomes apparent. This may be largely accomplished by a more complete harnessing of the large number of our water powers now going to waste. Recently I have estimated the value of coal saved yearly by only four hydroelectric developments located along the Canadian boundary to be in the neighborhood of $3,000,000.

CALCULATIONS ON DEPRECIATION

In reference to estimates concerning depreciation of plant, I agree with Mr. Doherty that in order to arrive at a reasonable figure covering the entire property, it is essential that the useful life of each element composing it be taken up in detail, rather than resorting to the frequent practice of using a blanket depreciation rate covering the complete plant. It is also properly conservative to use a depreciation rate which is the result of the investment of the annual depreciation fund at prevailing savings bank interest rates during the period of the estimated useful life of the portion of plant under consideration.

J. Lester Woodbridge (by letter): I cannot permit to pass unchallenged Mr. Doherty's brief reference to the use of storage batteries as a protection against interruptions of service in hydroelectric systems. I hardly feel that a sufficiently thorough investigation of this subject has been made to warrant so sweeping a conclusion; in fact statements in other parts of the paper indicate that this conclusion could not have been based upon very complete data.

The author practically admits the necessity of providing some means for insuring continuity of service in the class of systems discussed, and the problem resolves itself into a determination of what character of apparatus will give the desired insurance at the least annual cost including operating expenses, depreciation, and fixed charges. In order to solve this problem it is of course necessary to have accurate data as to the annual cost of the different schemes proposed. The author appears to favor an auxiliary steam plant for this purpose, but in stating that he has never seen an efficiency curve on boilers, showing their economy from no load to full load, he has apparently admitted that he lacks at least one factor necessary to a complete solution of the problem. In cases where the cost of fuel is high and the character of service to be rendered requires that a steam plant shall be kept constantly ready to take an emergency load, this factor may be a most important one.

It is, however, the figures on the other side of the equation; that is, the annual cost of a stand-by battery, that I would particularly discuss, as I fear that Mr. Doherty's statement has been based on more or less misleading information.

The use of a storage battery for purely stand-by service is, in this country at least, of comparatively recent origin. In the early days of storage battery history there was no such thing as a purely stand-by battery. The man who made a considerable investment for a storage battery plant was not satisfied unless the battery was kept constantly at work. He was satisfied to install three generating units in his power plant and permit one of these to lie idle as a spare unit from January 1 to December 31; but not so with the storage battery. That must be worked or he was not getting the return for his money. A large part of this work was of course legitimate and was work which a storage battery could be called upon to do economically, using the word in the broadest sense of the term; but a very considerable part of this work was in many cases absolutely unnecessary and could have been handled much more economically by the generating units. In either case, however, the work done was far in excess of that required from a stand-by battery. On this account the first cost and maintenance charges for a battery which is limited to strictly stand-by service will be considerably less than past experience would indicate, and the great bulk of the data on which we might draw for information as to the commercial results of the operation of a storage battery is therefore quite useless in the present problem.

Within the last year or two there have been put into service several large storage battery plants especially adapted for this class of service. The plates are of a type designed to give the maximum capacity, particularly at high rates of discharge, with minimum weight, floor space, and first cost. These batteries are not designed to handle heavy peak discharges every day, and are not so used, but are held strictly in reserve ready to take up the load in case of any failure in the generated power. Such discharges occur only at comparatively infrequent intervals and although the question of maximum durability under heavy work has been subordinated to other considerations in the design of the plate, the depreciation and maintenance of these plants will undoubtedly be exceedingly low. Information on investment cost for this type of battery is, ofcourse, available and shows an appreciable reduction from that for the standard types.

I feel, therefore, that so far as the question of dollars and cents is concerned, the comparison between the storage battery and other means for insuring continuity of service should hardly be dismissed with so brief and sweeping a statement as the author has made. There are, however, other aspects in which this problem must be considered. The conditions to be met vary widely in different cases. There are, of course, situations in which the storage battery is not the proper solution of the problem, but the conditions, as shown by Mr. Doherty's paper, vary over so wide a range that conclusions arrived at in one particular case can rarely, if ever, be applied to another. In some cases it is possible that a combination of both storage battery and steam- or gas-engine-driven generating machinery may be successfully employed. The character of service required will also have an important bearing upon the problem. To quote Mr. Doherty's own words:

> The importance of continuity of service varies in degree with almost every customer served. To some industries a mishap which causes even a fall in voltage or a change in frequency may be a serious matter.

I believe that many cases will arise in which the storage battery will be found the only means for producing the desired results and will be adopted even in the face of increased financial outlay.

The above remarks apply to the application of a storage battery for strictly stand-by service. There is, however, a wider field than this for the storage battery in connection with hydroelectric developments, for carrying occasional peak loads beyond the capacity of the generating machinery. So long as the power marketed does not tax this capacity at any time, there will be no excuse for such service from a battery; but as soon as the limit of the power development is reached, there will in many cases be profitable situations for storage battery installations for increasing the station capacity where further increase in the water power development would be impossible or prohibitively expensive, and the length of the peak so short as to render steam generation highly inefficient.

W. E. Winship (by letter): That portion of Mr. Doherty's paper dealing with methods and equipment to insure continuous service is of special interest to me, but I wish to take exception to the statements that the investment and cost of maintaining storage batteries practically preclude their use for this purpose. If absolutely continuous service is required their use is necessary, as they offer the only practical instantaneously available source of electric power.

The entire storage battery situation has radically changed during the last few years. Experience has taught what constitutes proper operating conditions in order to obtain a long life of plates and other parts. Progress has been made in the direction of design for the different service conditions. Costs of manufacture have been considerably reduced. In particular, batteries for stand-by service have been made considerably cheaper, and their cost of maintenance is extremely small.

In my opinion it is almost impossible to make general deductions that will hold good for even the majority of water-power situations. The available water-flow may be ample in some cases; it may be insufficient in others at least during a portion of the time. It is probable that in all cases the latter condition will be true eventually, though this may be far removed and a temporary solution will often be the only justifiable one. There is at least one storage-battery plant—probably there are many others—installed in connection with a water power, whose entire cost was saved during its first year of operation, by shutting down the steam plant which had been used to take the peaks. This particular battery has been in service over six years, with no renewals and with little prospect that any will be required for several years more. I have intimate knowledge of a number of battery plants of from seven to nine years old without plate renewals and with none being required for several years. I have strong grounds for asserting that the pure lead Planté type of positive plate is good for from seven to nine years of life in hard service, and that under stand-by conditions it will last much longer. Planté negative plates properly made will have conservatively at least double the life of positive plates. It may be admitted that many engineers have the opinion of battery maintenance cost expressed in the paper, but they should inform themselves in regard to the performance of some of the makes of batteries with which they may be unfamiliar.

A comparatively recent development is the use of regulating storage batteries whose duty is controlled by the variation of the alternating-current load. This function, in addition to their available discharge capacity for a limited time, makes them an extremely valuable adjunct to a plant if the load is variable. Incidentally, both voltage and water-wheel regulation are obtained; these are not small points in themselves, while the plant and line capacity are both increased.

I am surprised at the apparent lack of faith in the reliability of transmission lines shown in the oral discussion of Mr. Doherty's paper. Numerous transmissions of moderate length and voltage are satisfactorily serving public utilities all over the country; and with the better insulation and lightning protection now available, it would seem that the proper step, in those cases where trouble is experienced, would be to improve the lines. With duplicate lines and facilities for rapid testing and switching, it should be practically possible to reëstablish service in a very short time. The investment corresponding to the duplicate lines need not be prohibitive, as the duplicate lines could be designed to carry the load at maximum economy with both lines in service, but with a greater drop in voltage when but a single line is operated.

Holding either a steam or water power plant in reserve but ready for instantaneous service seems to me an extremely inefficient way to utilize apparatus; furthermore, it would not under any condition insure against a short interruption of power. Instantaneous readiness for service could scarcely be obtained with a steam plant, as there would necessarily be an appreciable interval before the boiler could respond to the sudden demand. Water wheels might respond more quickly, but their governors are notoriously sluggish, especially with low heads. Some instantaneously available source of power is necessary if momentary interruptions are to be avoided, and storage batteries form the only practical apparatus for the purpose. If the water power is insufficient to carry the total load, necessitating reinforcement by another generating plant, it would of course be much simpler to throw an additional load on the operating steam plant than on such a plant standing idle; even in this case, however, there would be grave danger of a short interruption of power without a storage battery.

Francis Blossom (by letter): Many engineers will not concur in Mr. Doherty's statement that

> The problem of reliable service on long transmission lines is much further from solution than all of the other problems that have done so much to contribute obstacles to rapid development.

The use of a long transmission line does not necessarily entail interruptions exceeding in frequency those occurring on the multiplicity of feeders frequently served from a steam station located nearer the point of power consumption.

The continuity and reliability of service supplied over a transmission line is largely a question of the mechanical and electrical strengths of the line. Assuming proper design, mechanical strength is a function of purchased safety-factors, and the same is true—but to a lesser extent—of electrical strength, which, however, is more subject to stresses of unknown magnitude.

Mr. Martin has stated that some performance figures would be given with respect to the 15,000 kw. power supply furnished to the Pacific Gas & Electric Corporation over the transmission line of the Stanislaus Company. These show an uninterrupted line delivery over a ten months' period—from February 1, 1909, to December 1, 1909—of a 100-mile transmission line of the Sierra & San Francisco Power Company, supplying a maximum demand of some 15,000 kw. from the hydroelectric station of about 20,000 kw., on the Stanislaus River, in the Sierra Mountains, to a sub-station of the purchasing corporation at Mission San Jose. The conductors are of 2/0 copper, six-strand, hemp center, spaced about 9 ft. minimum vertical and 16 ft. horizontal distances apart on an unsymmetrical triangle, supported by suspension insulators of five elements on single-circuit, pyramidal, galvanized steel towers, averaging six and two-thirds towers per mile.

The operating performance is tabulated as follows:

TABLE I

	Hours	Minutes	Percentage
Total period of delivery of power to purchaser......	6709	22	92.26
Total period of non-delivery of power due to cessation of purchaser's demand..........................	539	21	7.42
Total period of non-delivery of power due to interruptions caused by troubles of any nature in the generation of power..........................	23	17	.32
Total period of non-delivery of power due to interruptions caused by troubles of any nature in transmission line..........................	0	0	0.00
Total elapsed period (10 months)..................	7272	0	100.00

Philip P. Barton (by letter):

METHODS TO INSURE AGAINST INTERRUPTIONS OR TO LESSEN THE HARMFUL EFFECT OF INTERRUPTIONS

In a general manner, the transmission system by means of which Buffalo and Tonawanda are supplied with electrical energy from the plants of The Niagara Falls Power Company and Canadian Niagara Power Company is indicated herewith, in Fig. 1. The installation may be described as consisting practically of a closed-loop arrangement of transmission lines passing through three great hydroelectric generating stations and through three sub-stations—two in Buffalo and one in Tonawanda—in such a way that any or all of the sub-stations may be supplied in either direction from any one or all of the three generating stations. The system as shown was completed substantially in 1907, although the third Canadian circuit was not constructed until 1908. In the 30 months during which this system has been fully in operation, there have been two interruptions to the entire power service to Buffalo, each caused by lightning. On one of these occasions, all of the American and Canadian transmission lines were short-circuited almost simultaneously by a wide-spread lightning storm. On the other occasion, the entire service would not have been interrupted except for the fact that the American plant was completely shut down for repairs to the tunnel at the time when the lightning short-circuit occurred. From July 24, 1908, to this date (January 3, 1910), the continuity of Niagara power service to Buffalo has not been broken.

The following is a statement in detail of the complete interruptions to the Buffalo service since January 1, 1905:

TABLE I

1905	
Jan. 25,	Short-circuit in transformer in customer's sub-station.
Feb. 23,	Short-circuit due to mistake of electrical fitter at generating station.
June 5,	Wire thrown across transmission line by telephone lineman.
June 5,	Transmission line short-circuited by lightning.
July 17,	Transmission line short-circuited by lightning.
July 19,	Transmission line short-circuited by lightning.
July 27,	Short-circuit in step-up transformer at generating plant.
Aug. 3,	Transmission line short-circuited by lightning.
Aug. 10,	Bale wire thrown across transmission lines.
Aug. 30,	Transmission line short-circuited by lightning.
	Total...10
1906	
Jan. 4,	Short-circuit on transmission line caused by wind storm.
Jan. 5,	Defect in cable insulation at generating plant.
Apl. 14,	Mistake in switching at generating plant.
Apr. 29,	Transmission line short-circuited by lightning.
May 4,	Transmission line short-circuited by lightning.
June 8,	Transmission line short-circuited by lightning.
Aug. 3,	Transmission line short-circuited by lightning.
Aug. 3,	Mistake of attendant at customer's sub-station.
Oct. 10,	Tree broken down across line by heavy snow storm.
	Total... 9
1907	
Jan. 20,	Short-circuit on transmission line caused by wind storm.
Apl. 24,	Mistake of attendant at customer's sub-station.
June 4,	Tape line thrown across transmission line by civil engineer of a railroad company for purpose of measuring elevation of conductors.
	Total... 3
1908	
June 22,	Transmission line short-circuited by lightning.
July 24,	Transmission line short-circuited by lightning.
	Total... 2
1909	None
	Total... 0

Few of the above interruptions lasted more than 5 min. In many cases the service was resumed within 2 or 3 min.

While the experience of The Niagara Falls Power Company may not be especially helpful to those who are endeavoring to transmit energy to great distances at very high voltages, members of the Institute may be interested in the statement that the central station lighting companies in Buffalo and Tonawanda scrapped their steam plants more than 11 years ago and have not burned a pound of coal for power purposes since 1898; and that the railway company operating substantially all of the urban and interurban trolley service within 30 miles of Buffalo keeps its steam plants shut down and closed up except during the winter months, when its peak load requirements cannot be supplied economically from a hydroelectric plant.

In dealing with the subject of safeguards against interruptions to service, I think that in many cases too little consideration is given to the necessity of building up an efficient operating organization. One of the important ways in which insurance of continuity of power service is sought is by connecting up into a common network several generating plants with a number of inter-connected sub-stations. Operating complications and opportunities for mistakes multiply very rapidly with this process, and the problems of selecting and organizing and training operating forces to handle successfully such plants are often of far greater importance than the problems of design and construction. The variety of possible emergencies in a modern power installation is very large. To prevent these emergencies, to predetermine and carry out correct methods for dealing with those that cannot be prevented, and to meet with prompt resourcefulness and coöperative team work those that cannot be foreseen, require the same kind of preparedness and discipline in an operating organization that are exhibited by a successful army in the field, and these qualities are to be acquired by similar methods in each case. I think that many engineers would be surprised, were they to make a critical analysis of the operating records of some large power installations, to find what a large percentage of accidents must be charged directly or indirectly to defective organization.

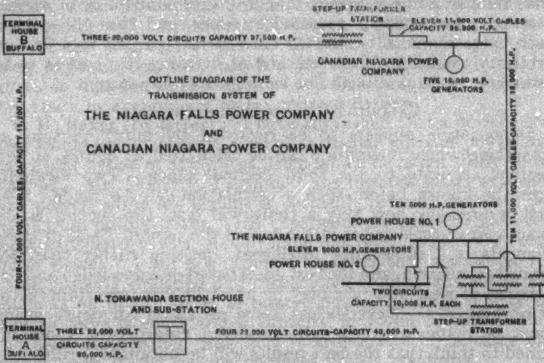
TERMINAL HOUSE B BUFFALO
THREE-22,000 VOLT CIRCUITS CAPACITY 37,500 H.P.
STEP-UP TRANSFORMER STATION
ELEVEN 11,000 VOLT CABLES CAPACITY 36,300 H.P.
CANADIAN NIAGARA POWER COMPANY
FIVE 10,000 H.P. GENERATORS
OUTLINE DIAGRAM OF THE TRANSMISSION SYSTEM OF
THE NIAGARA FALLS POWER COMPANY
AND
CANADIAN NIAGARA POWER COMPANY
FOUR-11,000 VOLT CABLES, CAPACITY 15,200 H.P.
TEN 11,000 VOLT CABLES-CAPACITY 38,000 H.P.
TEN 5000 H.P. GENERATORS
POWER HOUSE NO. 1
THE NIAGARA FALLS POWER COMPANY
ELEVEN 5000 H.P. GENERATORS
POWER HOUSE NO. 2
TWO CIRCUITS CAPACITY 10,000 H.P. EACH
N. TONAWANDA SECTION HOUSE AND SUB-STATION
TERMINAL HOUSE A BUFFALO
THREE 22,000 VOLT CIRCUITS CAPACITY 30,000 H.P.
FOUR 22,000 VOLT CIRCUITS-CAPACITY 40,000 H.P.
STEP-UP TRANSFORMER STATION

FIG. 1

PENALTIES FOR INTERRUPTIONS OF SERVICE OR INSURANCE AGAINST INTERRUPTIONS

The only point I wish to make on this subject is the desirability of keeping contractual relations between a power company and its customers as simple as possible. I doubt whether any penalty that it is practicable to get into a contract will have any appreciable effect on the continuity of service from a hydroelectric power plant. In most cases, the service will be the best that the ability and resources of its management can produce, irrespective of the question of penalties. I think that the common expedient of a rebate of charge during periods of interruption, and perhaps for an agreed period in addition thereto, will meet the requirements of nearly every ordinary case. The plan described by Mr. Doherty seems to be ingeniously complicated. As I understand it, it simply means that the parties have agreed that to insure continuity of service a steam plant must be operated at times, and that the cost of such operation is to be divided between the parties in a certain arbitrary manner. If the method of dividing the cost is to be arbitrary, perhaps it might be simplified to advantage.

CALCULATIONS ON DEPRECIATION

Depreciation appears to be regarded by many persons as something whose magnitude can be calculated in figures of percentage accurate to the third decimal place. Two elements must be known before such a calculation can be made. The first is precisely how long a thing will last; the second is the exact cost of replacing it at the end of the period. Each of these elements is a subject for intelligent guessing rather than for refined calculation, and the best guess based on knowledge and experience of wear and tear may be upset by the uncertain factor of obsolescence. Nevertheless, some provision for depreciation must be made in every well-considered enterprise. I am inclined to think that the best results will be obtained if rules and percentages are abandoned. No two cases are alike. Each must be treated by itself. I am of the opinion that the amount to be set aside annually for depreciation should be determined somewhat arbitrarily by the application of common-sense to conclusions reached after a free and thorough discussion by the engineering and accounting and financial representatives of the enterprise. In a prospective development any figure for depreciation is necessarily a guess. In a going concern the financial situation must be considered quite as much as the physical situation in setting up reserves for depreciation.

I have been asked to give some figures on depreciation based on the actual experience of The Niagara Falls Power Company, and have had prepared a statement of the actual expenditures for maintenance and repairs and betterments for the electric generating plant and for the hydraulic motive power plant covering the period from January 1, 1900, to December 31, 1909.

The electric generating plant consists of twenty-one 5000-h.p. generators with switchboard equipment, etc. The plant is now apparently in about as good condition as when it was new. About 40 per cent of the switch gear may be described as obsolescent, although for practical purposes it is more efficient than when it was installed. At a convenient time, however, it doubtless will be replaced with modern equipment. The actual annual expenditures on this plant for maintenance and repairs and betterments have been slightly under three-fourths of one per cent of its original cost. This includes complete new windings of improved design for the armatures of seven of the generators. It is interesting to note, in this connection, that generator No. 1 put in commercial service in 1895, has required practically no repairs and exhibits no visible signs of depreciation.

The motive power plant consists of twenty-one 5000-h.p. turbines with shafting, governors, headgates, oil pumps, oiling system, etc. The actual annual expenditures for maintenance and repairs and betterments have been slightly under two per cent of the first cost of the installation. The entire plant has been kept in the best possible physical condition, but it is probable that ten of the turbines will be rebuilt within the next few years in accordance with improved designs.

C. H. Baker (by letter): I have always felt that a power engineer leans, unconsciously, toward particular kinds of power and particular types of apparatus, from which he is not likely to be weaned. Mr. Doherty, I assume leans towards steam as a motive power, while my leaning is decidedly toward the power derived from falling water. His experience undoubtedly has been most satisfactory with steam; mine has been decidedly so with water power. I am not disposed to admit that a water-power plant properly designed and constructed requires any steam adjunct at all in the sense of reserve power, although it may be well to have a considerable capacity in steam to carry either the daily fluctuating peak in a mixed service or to carry the winter peak if the service produces such a condition.

I do not recall a properly designed water-power plant where a steam plant has been introduced as a reserve. It is very common to find auxiliary steam plants in connection with water-power plants, but they owe their existence to the fact that they preceded the water-power plant, the steam plant being retained as an auxiliary either to carry the peaks or as a protection against uncertain service, as a wiser measure than to reduce it to scrap and practically get nothing for it. My belief is that a water-power plant can be so simply designed and so well constructed that even with a long transmission the interruptions to service and the fluctuation in voltage will compare favorably with the service rendered by any steam plant.

I believe that the Snoqualmie Falls plant which supplies Seattle, Tacoma and Everett in the state of Washington, has no equal from any point of view in the shape of any steam power plant in operation on the Pacific Coast. The Snoqualmie plant operates year in and year out with scarcely a second of interruption, and although the transmission lines carry the railway circuits as well as miscellaneous power and lighting circuits, the variations in the voltage curve are almost limited to the thickness of the curve itself. The success of the Snoqualmie plant as a reliable power agency is due: first, to the absence of a flume which the river itself takes the place of; secondly, to simplicity of wiring and switching arrangements, both at the primary and terminals; and, thirdly, to a well built duplicate transmission line following a right-of-way cleared beyond peradventure of all trees and other features which might challenge the continuity of the service.

It is particularly important that the transmission conductors whether of copper or of aluminum, should be stranded cables. I prefer aluminum, principally because of its lightness. My judgment is that the extra investment necessary to incorporate an auxiliary steam plant—if incorporated in the water-power plant itself—in the shape of duplicate pole lines, extra conductors, concrete or steel towers, a spare unit at the generating station, the best type of insulators and lightning protection, and spare transformer units at both the primary and subsidiary end will lay a foundation for a service as reliable as that offered by any steam plant. I also believe that flumes should be replaced by excavated canals or tunnels wherever possible.

I concede, of course, that no two water-power situations are alike. Among them all there will be a few conspicuous for desirable features with which nature has endowed them. There will be others which by their very nature will be almost impossible situations. Then there will be a large number having only average merit. If one could design his own water power he would avoid extremely low heads, meaning that an unusually large volume of water per horse power would have to be handled for power production; and he would avoid extreme high heads where great pressures and high velocities would be encountered, requiring great and unusual strength of apparatus, and developing features inimicable to good regulation. The ideal head would neither be 10 ft. nor 3000 ft. but about 500 to 600 ft., thus calling for impulse wheels in place of turbine wheels.

A word with reference to the relation of power companies in general to the public. An asset item of as great value to a power company as its boilers or its water wheels is that of popularity. This item affects very materially the earnings of a company and the value of its franchise rights, which emanate from the people. A good plant and a poor and short-sighted management may not be as good an investment for the bondholders as a poor plant presided over by an able and courteous management which is ever ready to doff its hat to the public. The company must have public confidence, and the eye of suspicion must not rest upon it in regard to any of its measures or actions. If the public knows that the company is in league with corrupt councilmen for the purpose of gaining lasting and unreasonable privileges, then every person in the community will disparage it at every opportunity.

The disposition quickly to repair troubles, to adjust complaints as to bills, and to not ask too much of the public in way of franchise privileges is in line with Mr. Doherty's remarks, and my reference is simply to emphasize what he has said upon the subject. I have witnessed the situation of a water-power company being out of commission due to a fire, and the opposition company endeavoring to take advantage of the situation by offering its service at once, coupled, however, with the condition that long-time contracts be entered into. The afflicted company was so popular, however, that stores, residences, etc., burned candles for about 36 hours rather than entertain any propositions for relief whatsoever coming from either electric or gas light opponents.

The ideal situation in a water-power business is a water power company serving large industries like flour mills, steel works, etc. Mr. Doherty's optimism makes it clear that most water-power companies may be able in the future to select their own business. This is the kind of business that such companies would naturally prefer, for the reason, as he stated, that the service may be for some purposes less refined than where lighting and street car services are involved. Besides thus developing an uncomplaining class of customers, the situation is simplified by having fewer circuits, fewer meters, fewer accounts to keep and fewer although larger collections to make. A mutuality of interest may at the same time be developed by the power company investing in the securities of this class of customer which it may serve.

If a central station handling mixed business of the community exists, the power company may furnish it a certain allotment of power covering its base load, and not exceeding say one half the average peak. If there is an interruption in service under this condition it would only be partial, as the central station would have its steam plant in operation, and the patrons of the company during the period of affliction could get along with half their necessary lighting, and the street car service could be reduced temporarily one half. The power thus sold by the hydroelectric company to the central station should be accepted by the central station company, subject to the conditions which experience teaches are likely to obtain, and the price should be made accordingly. There should be no penalties, which only promote friction and bad feeling. The hydroelectric company will maintain no better behavior due to any code of penalties. In such an event it is the greater sufferer by virtue of losing reputation and revenue.

If the hydroelectric company desires to handle the mixed business of the central station, it should preferably have its own central station do its own distributing as well as generating. and deal directly with the members of the public without the intervention of another company. In this way the consumer feels that he is getting his power first hand, and at more nearly its reasonable value, and he is also in a position to know whom to commend for a good service and whom to censure and have recourse upon for bad service.

H. F. Parshall (by letter): I have been called upon to carry out or report on very many power installations, the majority of which have been founded on more or less sound commercial lines. In many cases, however, the rate of growth of demand for power has been overestimated. In the design of a central power installation it is necessary to take into consideration in the original arrangements the character the installation may ultimately assume. In the case of hydroelectric undertakings it frequently happens that a good deal of the initial investment has to be on a scale to provide for the size the installation may be expected finally to grow to. The same remark applies in certain details, but to a lesser extent, to steam installations. In both cases it has been found as a matter of practical experience that the demand does not arise before the ability to supply it and growth is frequently very slow, even after the supply has been demonstrated to be both advantageous and reliable. It follows, therefore, that any type of power installation is likely to be subject to heavy initial interest charges. In some instances engineers have been over-sanguine as to the time required for completion, over-sanguine as to the prices that could be realized with any reasonable rate of growth, and over-sanguine as to the time such growth would be sufficient to earn fixed charges.

Looked at from a financial point of view, the time-element is the principal deterrent. Any hydroelectric installation sensibly located, is, in the long run, likely to become a valuable property, although the original projectors may not be the ones to reap the benefits of the undertaking. Owing to many engineers having overestimated the possible earnings of power installations, many financial houses have become extremely pessimistic on the subject. At the present moment I think it may be fairly stated that, from a financial point of view, many of the hydroelectric power installations in the United States are of the future rather than of the present. But there can be no doubt as to the ultimate value of this class of undertaking. A paper of the character of Mr. Doherty's is of especial value in that it should tend to restore an equitable balance between the optimism of the engineer and the pessimism of the banker.

I recently heard the opinion expressed by a banker who is associated with the development of hydroelectric power schemes in Switzerland, that eventually such installations had won out, and that hydroelectric undertakings were a good class of security to have on a banker's shelf, since they were constantly appreciating in value. This opinion is based on installations that have been working for some time, and on the smaller class of installation where the initial capital required for future development was comparatively small.

In building a railway it is frequently possible to install a structure more or less temporary, so that the capital charges are small, until such time as the traffic justifies something more permanent, so that "scrapping" at the opportune moment is of less importance than the interest charges that would have been incurred on a permanent class of installation. Unfortunately, this course cannot be followed out in a hydroelectric installation, and, as stated in the beginning, this introduces the all-important factor as to time.

I think most of the hydroelectric installations have been well designed, although in some cases greater attention should have been given to the duplication and stability of lines. Here again, time-element and capital have to be considered.

In many installations the question of a stand-by plant has to be seriously considered, and I do not know that there is any general solution in view. Both gas engines and oil engines are extremely expensive to install but are efficient in the matter of fuel consumption. The steam-turbine station is the cheapest to install and maintain, but in some cases the stand-by charges are considerable.

Generally speaking, I do not suppose that my opinion differs at all from that of all other engineers; namely, the less the extent of stand-by plant, the less the likelihood of its being called into commission, and the more attractive the hydroelectric installation. Once the supplementary stand-by power stations become a necessary part of a water-power scheme, the commercial result becomes problematical and often evanescent.

Having regard for the natural conservatism of the banking fraternity, my advice is that engineers should be especially careful to catalogue the risks as fully and as explicitly as the prospective and possible advantages, so that a useful field is not needlessly handicapped by preliminary mistakes.

J. F. Vaughan (by letter): A feature too often slighted in hydroelectric plant design, but essential to the best economy of operation, is some adequate provision for recording the flow of the stream. The usual method of determining flow by guage heights taken once or twice a day without reference to the rise or fall of the river at the time of observation or the possible changing of the cross section of the river is often inaccurate or a wholly unreliable indication of the power of the stream, or of capacity for further development by storage, steam supplement, or otherwise.

Wherever possible, measuring weirs should be provided and where too costly, or otherwise impracticable, every other available means of determining the stream-flow or of checking other measurements should be taken; as for instance by:

1. Calibration of the dam-crest as a weir, using a continuously

recording gauge to determine the height of water above the crest and the variation of the pond-level.

2. Calibration of sluice gates, fishways, etc., in the same manner.

3. Calibration of the water wheels themselves to determine the flow through them at different gate openings, and recording of backwater level.

4. Calibration of flume or canal at a given section by current meter or weir, and use of a recording water-level indicator.

5. Measurement of pipe line or penstock flow by pitot tubes (preferably recording).

6. Indication of flow by venturi tubes, or even by friction head losses measured at sufficiently remote points in the pipe, etc.

These should be supplemented by meteorological observations wherever there are insufficient government stations.

Not only should designers provide every reasonable facility for keeping the most accurate records of the power available and used, but operators should see that the records are properly kept and the accuracy of the methods maintained; for without such records, neither can the owners get the maximum return from their equipment, nor can they properly determine the true value of the power nor the extent to which it may be further developed.

E. C. Brown (by letter): The impression generally prevails that the Federal Government is unfavorable to the liberal development of water powers. This, perhaps, is taking an extreme view of the attitude of the authorities at Washington. But, be this as it may, the effort now making by Government officials and an association devoting itself to the conservation of the country's natural resources cannot but exert a favorable influence on our water courses, since the devastation in recent years of vast tracts of woodland has very appreciably affected the constancy of developed water powers. Let us hope that any retardation, by reason of the general policy of the Federal Government against development of water powers, may be counterbalanced by the efforts now making for husbanding woodlands so essential to the permanency of streams.

CALCULATIONS ON DEPRECIATION

Under Calculations on Depreciation the writer would submit that hydroelectric plants should be built with at least three views always in mind:

1. Thoroughness to insure stability of dam and all work connected therewith. Inferior construction in this field of operation, probably more than any other, might lead to most disastrous consequences, as well as loss of considerable investment.

2. Construction with a view of obtaining every foot of available head, even though initial investment may be increased.

3. A factor of safety is generally a wise policy, when estima-

ting on water power development, by making a liberal allowance for cost of construction on the plant and figuring the dependable stream-flow a fair percentage below that which seems warranted by the measurements and statements made to the engineer by "old inhabitants of the region."

With respect to 2. About 10 years ago I was associated with a hydroelectric development that suffered a loss of nearly 15 per cent in possible power development because of the unfortunate decision to save a matter of $200,000 in flume construction instead of tunnel development which should have been made.

J. H. Wilson (by letter): In my opinion the investing public's distrust of hydroelectric projects is more fully justified than we might like to admit. The arbitrary deductions on the engineer's estimate made by those who have had experience with these investments is, I think, a serious matter. It shows that in many cases the engineers who make these estimates are professionally incompetent or do not realize their moral responsibility.

To be specific, large sums of money have been invested on engineers' reports in which the minimum stream-flow was given at from three to five times the amount justified by the available reliable data. While the lengthy prospectuses might have some merit as works of fiction, as a basis for investing money with the expectation of getting a fair return, they were absolutely valueless.

Only under exceptional conditions as to market and cost of development is it commercially feasible to develop for more than the minimum flow of water, as the cost of auxiliary equipment which ordinarily must be provided renders the commercial success of the enterprise questionable.

Most streams in their normal condition do not provide a minimum flow that justifies very extensive development. We are thus brought face to face with the problem of artificial storage, which is absolutely necessary in order to conserve our water power. As to whether this should be done by public or private enterprise we may differ, but that it should be done admits of no question.

James Lyman (by letter): Public attention was first directed to the commercial possibilities of utilizing the water powers of the Country in 1895 when the Niagara Falls Power Company started its great power house. Since that time many water powers have been developed, and what was then a new and unexplored field of engineering has now been thoroughly worked out.

Water wheels of either the turbine or impulse type have been designed with a capacity up to 15,000 h.p. and for heads up to 1500 ft. and giving a brake horse-power efficiency in the largest size up to 90 per cent. The design and construction of masonry dams to withstand extreme flood water and all conditions of weather and climate is now as well understood as bridge building and other lines of civil and mechanical engineering.

Electric generators and step-up transformers with voltages suitable for transmission of many thousands of horse-power 150 to 200 miles with comparatively small energy losses, are of standard and reliable design.

The substantial steel towers well set on private right of way, the suspension link porcelain insulators of great mechanical strength and high insulating qualities, and the heavy stranded, hard-drawn copper cable ensure reliable service for long distance power transmission.

Before proceeding with any proposed hydroelectric development the following data should be obtained:

1. The fullest information should be obtained of the water flow throughout the year and over as many years as possible. The drainage area of the stream, the vegetation, timber lands, and character of the soil should be determined.

2. The available market for the power should be carefully canvassed, prices obtained, and actual or possible competition recorded.

3. To ensure the best returns on the investment, the hydroelectric company should control the lighting, electric railway or other power companies, using the water power developed. In other words, it should sell direct to the consumer instead of to a local company. A water power should not be developed until a good market is assured.

The majority of the water powers throughout the country are subject to a wide range of stream-flow. For two or three months of the year the flow may not be more than one-half the minimum flow during the balance of the year. To provide for this low-water season, a steam-turbine power house should be installed at the receiving end of the transmission line. The capacity of such power house should be, say, the difference between the power corresponding to the minimum flow during the year and the minimum flow during the nine or ten full months.

Such a power house would serve three important functions:

1. It would bring the capacity of power developed up to that corresponding to the minimum flow through nine or ten months of the year.

2. It would act as an insurance reserve on the system in case of possible interruption to the water-power service.

3. In long-distance transmission especially, one or more of the steam generator units could be kept running on the system, with very little energy loss, as a synchronous rotary condenser. By means of a Tirrill regulator in connection with its exciter, it could automatically maintain constant voltage at the receiving end of the line through a wide range of load and power-factor, the voltage at the water power house being kept constant regardless of the load conditions.

R. A. Ross (by letter): Until the engineer is willing to recognize that his services are only valued by the public according to the returns they give either in dividends or benefits, he will not fulfil his whole duty to the public, nor will he obtain that recognition which he deserves. Most engineers are too much wrapped up in the technical aspect of their profession, to the neglect of the commercial point of view, which has to do with the dollar. As a result, it is frequently remarked by financial men that engineers' estimates are notoriously too low. This is exemplified in the quotation given in the paper:

> We will not consider a water-power project unless, after doubling the cost, cutting the available power in two, and reducing the market price by 40 per cent it will show interest on the bonds necessary to issue.

This remark is a purposed exaggeration, designed to call attention to a situation. It is pertinent, therefore, to inquire wherein engineers' estimates have failed in this regard, and why. A number of reasons may be given, among others the following:

1. Estimates may be based on insufficient information, information which it is impossible to get, varying from that furnished by the oldest inhabitant as to the height of the water in a stream, up to reliable information by gaugings which have been carried out for a number of years. There is here a wide unavoidable margin for discrepancy.
2. The cost of certain parts of the construction, such as foundations, may be unknown and perhaps unknowable until "unwatering" takes place.
3. Estimates may be made during a period of depressed prices, and the project may be held over by the monied interests until prices have risen, when the financing is done on the old estimate.
4. Additions may be made to the enterprise which were not previously considered. It would appear that the cost of such additions would be allowed for in the mind of the financial man as extras, but it will almost invariably be found that he remembers nothing but the total amount of money originally extended or required and makes no allowance for extensions to the scheme. In fact he seems constitutionally unable and unwilling to recognize any other figure than that placed before him by the engineer for a stated case, whereas the development in its final form is entirely different.
5. Insufficient consideration to expenses other than those involved in the physical construction.

In the development of any project, the costs group themselves into two divisions:

a. Those purely engineering costs which cover the construction and equipment.

b. Those financial or business costs which cover the working capital, financing, deficits during the initial period of business, etc.

To illustrate this point, consider the following table which has been derived from an actual case of hydroelectric development under three schemes producing progressively larger amounts of power:

TABLE I

Data	Development		
	A	B	C
Construction			
1. Estimated cost of hydroelectric plant........	$1,895,225	$2,618,715	$3,694,386
2. Estimated cost of transmission lines and equipment............................	1,393,287	2,009,668	2,693,299
3. Estimated cost of sub-stations and equipment.	636,488	1,051,617	1,304,315
4. Total estimated cost of plant from items at market value.........................	3,925,000	5,680,000	7,692,000
5. Shortages, construction plant unavoidable extras, and mistakes, etc................	275,000	350,000	500,000
6. Total cost of physical equipment............	4,200,000	6,030,000	8,192,000
7. Engineering, with plans, supervision, and preliminary operation, say 5 per cent on Item 6..............................	210,000	301,500	409,600
8. Business, legal, insurance, and accident costs, allow..............................	75,000	100,000	150,000
9. Total cost of enterprise apart from financing.	4,485,000	6,413,500	8,751,600
Organization and Financing.			
10. Organization and promotion, charter, printing, brokerage, etc......................	75,000	100,000	150,000
11. Interest during construction, on Items 1 to 10 at 5 per cent on face value of bonds issued below par......................	329,979	480,706	649,267
12. Normal operating costs and bond interest in excess of gross earnings say for one year after operation commences...............	55,000	70,000	100,000
13. Securing business, extra advertising, canvassing, etc., during development period as above, allow..........................	22,000	30,000	40,000
14. Interest on Items 12 and 13 for say 1 year..	3,750	5,000	7,000
15. Total estimated cash expended until earnings equal operating costs plus bond interest..	4,968,729	7,117,206	9,697,867
16. Allowance for working capital.............	200,000	300,000	400,000
17. Total cash required......................	$5,168,729	7,417,206	10,097,867
18. Additional costs of Items 1 to 9 if development *A* is increased at different times instead of the larger developments being made at once..........................	——	$500,000	750,000

The engineering estimate will include Items 1 to 9, while the financial or business estimate should cover those from 10 to 17 inclusive.

The question then arises, in whose province is the estimating of such additional costs for which money must inevitably be raised? If left to the financial man, does he do his duty; or, failing this, does he not frequently take refuge in the statement that the engineering estimates are too low? I think that most engineers who have had to deal with these matters will recognize that the latter occasionally happens. It becomes a question, therefore, whether the engineer should not in self-defence consider these financial and business items in every case to the best of his ability, which if not corroborated by the financier with his wider experience, would at least serve notice upon him that they demand consideration.

The results in the illustration given may be summed up as follows, for equipment (*a*)

Total cost of physical equipment	$4,200,000.00
Total cash required for enterprise	5,168,729.00
Indebtedness to bondholders for above cash, bonds being sold under par	6,500,000.00

In this case it will be noticed that the indebtedness incurred exceeds the cost of the physical equipment by 55 per cent.

As stated by Mr. Doherty, financiers do apply the pruning hook to engineers' estimates, but of course not to the extent indicated in the quotation. The question arises whether this does not tend to the acceptance of schemes that have not been soundly estimated upon in preference to those which have? Where a careful conservative estimate is made the costs will be high, and the application of any arbitrary rule tends to eliminate it from favorable consideration on the part of the financier, and to give the preference to an ill-considered, ill-estimated proposition showing a lower cost. In other words, the whole matter hinges on whether the engineer is to be considered as a technical man dealing with the cost of the physical equipment only, or whether he is to be considered a business man competent to deal with the enterprise as a whole?

The education of the engineer has been neglected in his relation to business. It is about time this was recognized, and his responsibilities extended to the scheme as a whole. It is only when this education has been acquired and acted upon, that he will receive that respect from the business public and financial men that his profession warrants.

M. H. Collbohm (by letter): The combination of water power and irrigation projects mentioned by Mr. Doherty is interesting and new. For a number of years electrical power has been utilized in irrigation schemes, demanding, however, only a moderate amount of the total station capacity plants. Only recently have hydroelectric plants been built mainly for the purpose of supplying electrical energy for irrigation. Plants of such order are building with considerable station capacity, making it worth while to study the special conditions met with in this new line of work. In one of the developments of this nature with which I am associated, the generating station will be designed for a final equipment of 100,000 h.p. capacity.

The power for irrigation only is used for a certain period in the year comprising about 6 months. The new problem is, to find a market for the electrical power during the rest of the year. If commercial conditions would allow the use of the surplus energy for electrochemical purposes, such as fixation of atmospheric nitrogen, production of calcium carbide, etc., the question would be solved. However where such is not the case a market may be created by selling the power cheap enough to compete with coal or oil for heating purposes. This kind of market does not interfere with that for irrigation, as their respective seasons do not overlap. The sale of power for such a purpose would probably not bring any profitable returns, but it might cover the running expenses and fixed charges.

The problem of reliable service from long transmission lines is indeed not yet completely solved. However, with duplicate lines on modern steel towers and designed with due regard to the severest conditions likely to arise, with the suspension-type insulator, and frequently grounded guard-wires of copper-clad steel of proper size instead of ordinary galvanized steel, (as recently discussed by the writer) the reliability of a transmission line would be considerably higher than that heretofore obtained.*

The equipment outlined in the paper to provide against interruptions serves as an emergency arrangement to help out in case where an interruption has already taken place at some point in the system rather than a means to provide against such interruption. The usual cause of interruption to service in a station comes from lightning, atmospheric and internal, as produced by arcing grounds etc., entering over the transmission line. To provide against interruptions from this cause the electrolytic lightning arrester in connection with choke-coils is used satisfactorily. As a further protection to station apparatus, iron wires of high permeability can be substituted for the copper wires commonly used for high-tension leads in the power house. The protective action of the iron wires is based upon the skin effect produced by the very high frequency of lightning, thereby increasing the resistance of the iron wire enormously.†

It appears doubtful whether financial aid can be obtained to install equipments that are kept running only for immediate help in case of emergency. The fixed charges and operating expenses for such an equipment would tend materially to reduce the net income of the plant, because its operation is almost entirely unproductive. The money that would be required for such an equipment could possibly be spent to greater advantage on the transmission line, by running each line (in case of a duplicate circuit) on a separate right-of-way—which is very seldom done on account of high cost—and by providing more guard-wires of non-magnetic material and large cross-sections above the lines, grounded at every tower, to take care of the heavy currents inherent in atmospheric lightning, Lightning arresters at various points along the line would also materially reduce the danger to insulators and station apparatus.

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* See *Electrical World*, May 20, 1909.

† See article by the writer in the *Electrical World*, Dec. 2, 1909.

H. A. Storrs (by letter): Mr. Doherty's comments must appeal to all engineers in the West, who are in a position to know the effect of the present conservation movement on hydroelectric enterprises. His remarks are specially opportune just now, when the Government, through its officials, is calling for legislation and shaping policies looking to better control of our natural resources. It is true that in the past the Government's efforts to exercise control over water-power developments have been "largely misdirected or very generally misunderstood." Especially does this seem to be the case from the point of view of those who have found the former untrammelled conditions conducive to large gains on small speculative investments. It is not so much a matter of inducing public officials to take the "proper attitude" toward the development of our water powers, as of bringing about proper legislation to enable public officials to have some definite basis of authority on which to act. Our government officers, if given definite, comprehensive laws under which to work, and sufficient funds to enable them to perform the required work, can furnish a basis for future development of the water-power possibilities of the country that will give a stability to hydroelectric enterprises not possible under the present chaotic conditions.

As intimated by Mr. Doherty, there is need of "intelligent planning and engineering" to supplant the haphazard methods now in vogue, by which a partial development of the power possibilities of a stream is governed by a policy so ill-advised and short-sighted as to preclude, for a long time, any further utilization of the remaining power latent in the stream. If given proper authority and means, the states and nation, through their technical bureaus, could determine for each stream its ultimate power possibilities, including the approximate normal flow of the stream the opportunities for creating storage of flood flow, the sites for hydroelectric plants, etc. Estimates of cost and output of installations, based on such definite and reliable data, would be accepted by the men who have money to put into such enterprises, without the excessive "discounting" referred to in the paper. This discounting of the promoters' and engineers' statements has heretofore been somewhat warranted by the uncertainties on which many an attractive proposition has been based.

That an enterprise of the character under discussion may be undertaken on a very narrow margin of profit, if a proper examination has been made of the proposed water plant provided "the behavior of the stream is a matter of reliable record for several years", is, as implied by Mr. Doherty, worthy of notice.

It directs attention to the requirement that somebody should, for several years prior to the inaugurating of a new project, have been keeping a reliable record of the stream-flow. The systematic gauging of streams, in advance of any proposed commercial developments of power, will, of course, not be undertaken except by the state or national Government.

Engineers interested in hydroelectric and irrigation projects, should be the first to urge upon the Congress the making of adequate appropriations to enable the hydrographic branch of the Geological Survey to continue its stream measurements on all streams where a partial record has already been secured, and to extend its work to all the remaining streams as rapidly as new gauging stations can be installed. The topographic branch should also be provided with funds to enable it to continue its valuable work. Its contour maps furnish at once the basis for determining the profiles of streams and probable location of power plants, as well as possible reservoir sites. Not until complete data have been obtained can the Government intelligently determine the extent of the power possibilities of its streams, or make comprehensive plans for their utilization.

Referring to Mr. Doherty's statement to the effect that the efforts of the Government to exercise some control over water-power developments seem to be obstructing rather than encouraging such enterprises, the particular case presented below will serve to show what results may be expected if the present Government policy is enforced. The National Government can not, however, under the present laws, exercise general control over the waters of non-navigable streams, since this authority is vested in the separate states. But, under the Act of June 4, 1897, the Secretary of Agriculture has full power to regulate the occupancy and use of the natural forests. Through the Forestry Service, therefore, the Government deals with prospective power plants, storage reservoirs, conduits and transmission lines, so far as they may be located within the limits of the forest reserves. The essential features of the Governments policy as stated recently by the Chief Forester in a letter published in *The Outlook*, December 4, 1909, are: first, that the right to develop water power on the forest reserves shall be granted for a limited term of years and not for all time; secondly, that a reasonable charge shall be made for the privilege granted. The application of these principles is illustrated by the following case.

Under date of November 24, 1909, permission was granted by the Forestry Service, covering the occupancy and use of certain lands in one of the national forests in Colorado, for the storage reservoir of a power generating plant. The principal features of the terms under which the permit was granted are as follows:

1. Payment to the United States, annually in advance from September 1, 1909 until the beginning of use of the waters for

which permit is granted, at the approximate rate of one dollar per acre of reservoir area and five dollars per mile of conduit for the land occupied by such works.

2. Payment to the United States of a gross operating charge, based on the total electrical output of the plant per year, at the following rates per 1000 kilowatt-hours.

For the	1st year	2	cents
" "	2nd "	4	"
" "	3rd "	6	"
" "	4th "	8	"
" "	5th "	10	"
" "	6th to 10th years inclusive	12½	"
" "	11th " 15th " "	15	"
" "	16th " 20th " "	17½	"
" "	21st " 25th " "	20	"
" "	26th " 30th " "	22½	"
" "	31st " 35th " "	25	"
" "	36th " 40th " "	27½	"
" "	41st " 45th " "	30	"
" "	46th " 50th " "	32½	"

Certain deductions are allowed from the "gross" charge in case; (*a*), the title to part of the watershed has passed out of the United States; (*b*), the conduit is not wholly on government lands; (*c*), the power is derived in part from water stored in a reservoir constructed or owned by the permittee.

The following table shows the gross charges as determined for the project under consideration:

TABLE I.

Year	Output			Rate per 1,000 kilo-watt-hours	Annual charge
	Average kilowatt per day	Average kilowatt hours per day	1,000 kilowatt hours per year		
1912	3,000	72,000	26,380	2 cts.	$525.60
1913	5,000	120,000	43,800	4 "	1,752.00
1914	7,000	168,000	61,320	6 "	3,679.20
1915	10,000	240,000	87,600	8 "	7,008.00
1916	12,000	288,000	105,120	10 "	10,512.00
1917 to 1921	12,000	288,000	105,120	12.5 "	13,140.00
1922 " 1926	12,000	288,000	105,120	15 "	15,768.00
1927 " 1931	12,000	288,000	105,120	17.5 "	18,396.00
1932 " 1936	12,000	288,000	105,120	20 "	21,024.00
1937 " 1941	12,000	288,000	105,120	22.5 "	23,652.00
1942 " 1946	12,000	288,000	105,120	25 "	26,280.00
1947 " 1951	12,000	288,000	105,120	27.5 "	28,908.00
1952 " 1956	12,000	288,000	105,120	30 "	31,536.00
1957 " 1961	12,000	288,000	105,120	32.5 "	34,164,00.

3. Payment for all timber destroyed in the forest reserve.

4. Construction of the works to begin within 18 months from date of approval of the permit; construction to be completed

and operation of the works for the purpose intended to begin within 3 years from date of approval of permit.

5. The United States reserves, conditionally, the right to purchase power at as low a price as that allowed to any other purchaser.

6. The permit is not transferable.

7. The permit shall be forfeited to the United States, if the works be controlled by an unlawful trust, or if they be used in restraint of trade in the sale of electric energy.

8. The permit shall cease and be void at the end of 50 years but is renewable upon conditions not yet fixed.

For the purpose of comparing the Government charge to be paid for the water-power privilege with the annual income of the plant, the following table has been prepared showing what per cent of total gross receipts must be paid to the Government.

TABLE II.

RATIO (IN PER CENT) OF GROSS ANNUAL CHARGE TO GROSS ANNUAL INCOME

	Sale price of delivered power per kilowatt-hour				
	1 cent	2 cents	3 cents	4 cents	5 cents
1912	0.2	0.1	0.07	0.05	0.04
1913	0.4	0.2	0.13	0.10	0.08
1914	0.6	0.3	0.2	0.15	0.12
1915	0.8	0.4	0.27	0.20	0.15
1916	1.0	0.5	0.33	0.25	0.20
1917 " 1921	1.25	0.625	0.42	0.31	0.25
1922 " 1926	1.5	0.75	0.5	0.38	0.30
1927 " 1931	1.75	0.875	0.58	0.44	0.35
1932 " 1936	2.0	1.0	0.67	0.50	0.40
1937 " 1941	2.25	1.125	0.75	0.56	0.45
1942 " 1946	2.5	1.25	0.83	0.63	0.50
1947 " 1951	2.75	1.375	0.92	0.69	0.55
1952 " 1956	3.0	1.5	1.0	0.75	0.60
1957 " 1961	3.25	1.625	1.08	0.81	0.65
Average.........	2.085	1.0425	0.695	0.52	0.417

The table shows that for the 50-year period the average payment to the Government is about 2 per cent of the gross receipts, at a sale price or valuation of 1 cent for each kilowatt-hour, delivered by the plant, and about 1 per cent at a valuation of 2 cents per kilowatt-hour.

Applying these figures to the case in hand, assuming the average value of the electric power during the 50-year period to be 1 cent per kilowatt-hour, the gross annual receipts would be about $1,000,000 and the average annual payment to the United States would be $20,000.

In response to inquiry, asking what privileges and benefits were secured by paying to the United States the above "conservation" charge, the Forest Service replied as follows:

> The conservation charge is based on the value of the land occupied for the particular use to which the land is to be put, and on the special benefits the permitee received by reason of the care and administration of the natural forest including the protection of the watershed from fire and destructive cutting which materially affect the water sources.

The permit in hand was secured for the benefit of a project comprising a storage reservoir of 10,000 acres superficial area, of which 260 acres only were within the boundaries of a forest reserve. It follows that the annual payment of $1.00 per acre for the three years allowed for construction amounts, in this case, to only $260; whereas, if the entire reservoir had been in the reserve, a payment of $10,000 per year would have been required. It is presumed that the object of this heavy initial tax on the enterprise is to compel immediate construction of the works, thus preventing the power possibility from being held, undeveloped, for speculative purposes. Speculation in undeveloped water powers on forest reserves is still further guarded against by making the permits non-transferable.

The recommendations of the Secretary of the Interior, in his recent annual report, are generally in line with the present practice of the Forest Service, except that he would limit the life of the permit, or "easement", to 30 years, allow 4 years for accomplishing the first quarter of the proposed development, and require that transfer be made to the United States of the water rights necessary to provide for the estimated power development.

In view of the probability that, during the next decade electrical power will be applied extensively to the operation of railroads in the West, the policy and methods of the Government in exercising control over water powers located on government lands are subjects of great practical moment to the country at large. They deserve the careful consideration of engineers who are in a position to influence the trend of legislation and of public opinion.

Mr. Doherty's remarks under "collateral enterprises" are timely and specially applicable to present conditions in Colorado. Here the extensions of present irrigation systems, depending on gravity for conveyance of water, are becoming relatively more expensive each year, the earlier developments having taken advantage of the easier propositions. It is now more economical, in many cases, to resort to pumping. Electric motors driving centrifugal pumps are the ideal arrangement for such purposes, and pumping service affords a desirable load for a commercial generating station during the three or four months comprising the irrigation season. During the rest of the year, the generating capacity can often be used to advantage in meeting the extra demands for lighting and railway service. Rather than purchase power for operating the pumping plants, it is sometimes profitable to build generating stations using the power available at some of the "drops" which frequently occur in main canals of the gravity system. Or, if cheap fuel is at hand, steam generating plants may be warranted. A complete power and pumping system using the lowest grade of lignite was recently built by the United States Reclamation Service, the writer being responsible for its design and construction. The system is located near the North Dakota-Montana line, on the Missouri River, from which water will ultimately be pumped for irrigating about 25,000 acres. The generating station is close to the portal of the mine which was opened and is operated by the United States to supply fuel to this plant. The machinery installed comprises eight 250-h.p. boilers, three turbine generating sets aggregating 1100 kw. and two 225-h.p. steam-turbine pumping units. The main canal brings water to the plant from the pumping station located on the Missouri River and the water is lifted, at this point, to higher canals, thus providing abundant water for condensing purposes. The power is transmitted to five pumping stations, two of which are distant 28 miles from the generating plant. The boiler furnaces are designed especially for burning lignite containing 40 per cent moisture, 25 per cent fixed carbon and 25 per cent of volatile hydrocarbons, and show, under usual working conditions, an evaporation better than 6.5 lb. per pound of dry coal. The plant is out of commission about 8 months each year, but it is hoped that manufacturing establishments, such as flour mills, alfalfa mills, and paper factories, can be induced to locate where power can be furnished cheaply during the non-irrigating season. A beet-sugar factory, if built adjacent to the power house, so as to take steam directly from the installed boilers, would make a desirable combination.

Irrigation systems can hardly be developed on streams having as flat a slope as the Missouri River, namely, 0.8 of 1 ft. per mile, without resorting to pumping. Where the flood rise, occurring during the irrigation season, is as great as on the Missouri River, namely, 19 ft., and the banks very unstable, it is considered advisable to mount the pumps and motors on floating barges. These are rendered free to rise and fall with the river level, by conveying the water from the barge to the shore by means of steel pipes and flexible joints. Electrically driven pumps are, of course, best suited to installations of this kind, but in some cases it has been found desirable to place the entire steam plant on board a boat. The delivery of fuel to the floating plant is expensive compared with the delivery of electric power.

Fuel-consuming pumping plants and generating stations on irrigation projects will not ordinarily be resorted to, if electric energy can be had from a water-power plant located within reasonable distance.

The above description of a pumping system depending on fuel merely serves to emphasize the fact that irrigation requirements have already opened up a new field for the disposal of electric power from hydraulic plants in competition with power obtained from more expensive sources.

E. P. Roberts (by letter):

THE VALUE OF WATER POWER SECURITIES

The value of a water power is not intrinsic. As Mr. Doherty points out, it is affected not only by the present or the near future cost of furnishing energy in the desired form to the consumer, as compared with the cost from some other source, but, from the standpoint of the investor, by the probable future comparative cost.

THE RELATION OF WATER POWER DEVELOPMENT TO THE CONSERVATION OF OUR NATURAL RESOURCES

Although the work of the Federal Government and of some of the states relative to the conservation of natural resources, including potential water powers, is proving exceedingly beneficial and the data recorded by the Federal and State Engineers are of great value to the water power engineer, nevertheless the development of water powers has, in the writer's opinion, been hampered by law and by the rulings of federal and state authorities, the result being detrimental to the development of water powers and an economic waste. Federal or State control is necessary, and, in some cases, construction and operation by the Federal Government is advisable. Undoubtedly the benefit to the community resulting from the increased interest in the conservation of natural resources will be very great, but it seems as if there were a tendency to define the verb "to conserve" as meaning "to bury."

The conservation of large areas of timber land may be advisable, and in some cases undoubtedly is so; but in other cases it is a question whether throwing such land open to settlement is not more advisable from the standpoint of economics. Where land is used for forests only, the annual value per acre of the growth on such land is very small as compared with the possible value of farm products, provided the land is suitable for farming and there are transportation facilities. In most locations, if the land is suitable, transportation facilities will follow, if they do not precede, the development of farms. The cost of supervising, developing, and safeguarding forests is very considerable, and sometimes losses by fire are great. The number of persons employed for any given area is of course far greater when it is thrown open to settlement than when it is used solely as a forest. The above is not intended as an argument against conservation of forests, but merely against unwise conservation.*

COLLATERAL ENTERPRISES

Occasionally irrigation and boat canals must be considered. In a report made in 1905 by Mr. W. H. Abbott, relative to a

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*See article by R. C. Beardsley, *Southern Engineer*, June, 1909.

proposed power development in the Northwest, it was proposed to irrigate considerable tracts by electric pumping. The power was to be used for general purposes, so the pumping could be done at hours when other loads were at a minimum, thereby improving load-factor; in other words, provision for pumping for irrigation purposes was not to increase the cost of the water-power development. In some cases pumping could be done directly into the ditches, and in some places storage reservoirs would be obtainable at slight expense. A considerable amount of land along the bottom of the valleys was already irrigated, but there were many square miles at a slightly higher elevation which could not be irrigated except by pumping. Of course, anything which tends to improve the load-factor is beneficial, though the degree of benefit and consequently the rates which can be obtained depend upon storage capacity as well as upon other factors affecting each individual case.

THE UNFAVORABLE FEATURES OF WATER-POWER ENTERPRISES AND THEIR OPERATION

There are few proposed enterprises which require a more careful detailed investigation than a proposed water-power development. This investigation can only be made by spending considerable money. Unfortunately, many of those interested in such proposed developments are not willing, or are unable, to have such investigation made, with the inevitable result that many water powers have been financial failures. In some cases the first cost was far greater than that anticipated; in other cases the income was much less than the amount estimated.

In some cases there are legitimate reasons why the construction cost proves to be either greater or less than the estimated cost. For example, the estimate may be based on construction at times of average flow, work being done in the months that are shown by the records to be months of minimum flow, and especially least liable to floods. If the flow conditions are different from those anticipated, even though provision be made for deflecting the water to avoid damaging existing structures, nevertheless construction may be delayed, and often at considerable expense. On the other hand, if the season is unusually dry the cost may be materially decreased. In some cases the owners may postpone construction until the season advised by the engineer has passed and then insist, perhaps wisely, that construction be commenced. The changed conditions may, however, increase the cost, causing the engineers' reputation for accurate estimating to suffer.

Even when the first cost has been accurately predetermined, and possibly also the water-flow; minimum, average, and maximum considered by weeks, months, and years, and the possible and also the advisable storage capacity carefully investigated—nevertheless in many instances the market has not been accurately predetermined, and the result may be a failure.

RATING OF WATER POWERS

The mere statement that a water power has a specified rating is indefinite, and may be misleading, although comparisons are frequently based on statements of total horse power and cost per horse power, generally on the total rated horse power of the wheels installed. The following example indicates the fallacy of considering the value of a water power as based on the rating of the wheels installed

The proposed general development is to include three water powers to operate in conjunction. One power to have materially greater fall and also greater storage capacity at its site than the others, but the other two to be located lower down the stream and consequently to be benefited by the storage capacity of the upper power. Estimates were based either on first constructing and operating the greatest power, or on simultaneously constructing and operating all three. The output was estimated to be used as follows:

1. To operate an interurban electric road. The requirements of such a road can be predetermined with a fair degree of approximation, and the nature of such load is one having great momentary fluctuations.

2. *Lighting load.* The general nature of this can also be predetermined, the characteristic being a peak load during the early evening, the peak being greatly in excess of the load at other times.

3. *Factory power load.* The general characteristics of this are a fairly constant load and mainly day load.

4. *Pumping for town and village water works.* The greater amount consists of pumping into reservoirs, and consequently furnishes an ideal load both as to constancy and as to the practicability of such load operating only or mainly at times of minimum general load. The lesser amount consists of pumping into mains, but even such load is of excellent character.

The estimated resulting general-load curve has of course its maximum at the time of the overlapping of the factory-power load and the lighting load, which would occur early during winter evenings, especially during the Christmas holidays. Although the pumping load would presumably be off at such times, nevertheless safety required an allowance for a certain portion of such load. Also, although the interurban road would operate less cars then than on holidays during the summer, nevertheless it might also be operating under unfavorable weather conditions; this might not only bring up the average requirement but also, because of bucking snow, might result in excessive momentary fluctuations. The resulting general load curve would evidently be materially affected by any considerable modification as to any one character of load.

One estimate was based on the development of the greatest power operating alone, which evidently required that the installation in such power should take care of all conditions, and as electric generators have far greater overload capacity than turbines, therefore on account of the momentary fluctuating demand caused by the interurban road, the rated horse power of the turbines was estimated as being much greater as compared with the kilowatt capacity of the generators than would be required for constant generator load.

Another consideration was the probable result of installing storage batteries in the sub-stations of the interurban road. This would result in a power-house load having very slight momentary fluctuations, thereby decreasing the rated capacity of the generators, especially of the turbines, as the turbine rating would be approximately that required to operate the generators at constant load.

Another result would be that the capacity of the machinery in the sub-stations of the interurban road could be lessened, and the reliability of operation of the road somewhat increased; also the size of the transmission wires could be decreased, provided the size previously estimated was not already as small as the strength required would permit.

Another plan estimated was based on the use of storage batteries in the power house.

The plans above mentioned were made without reference to the operation of the other two powers referred to.

It will be noted that the useful output, and consequently the income, was practically the same in each case, but the rated horse power of the turbines was about in the ratio of two to three for the plan with storage batteries in the power house as compared with no storage batteries.

It might also be noted that the case was further complicated by the question whether the railway company, or the water-power company, should install storage batteries; and if the former installed them, then the water power company could afford to make the railway company a lower rate. It is evident that the decision as to what kilowatt capacity rates, and what comparative kilowatt-hour rates would be properly comparative, or equivalent, for each of such conditions, would require considerable study.

Estimates were also based on the development of the two smaller powers, considering whether either or both would take the peak load only, or would operate continuously; and whether they were to be placed in operation at the same time as the greatest power, or at some future date. This would obviously affect the horse power capacity of the turbine to be installed at the greatest power, but, nevertheless, the annual output of such principal power would not be affected except as the smaller powers might allow the operation of the largest power mechanism at rated rather than at part load.

Any specific case is complicated by such questions as the following: Will there be a market for secondary output, or such output as may be available at times, but is not expected, or guaranteed as being always available?

The question may also arise whether by increasing the water storage capacity, or by installation of steam power, or by making arrangements with existing steam powers, it may not be financially advisable further to guarantee the primary power or to take at least a portion of the secondary power out of such class and place it in the primary. Such changes may, or may not, materially affect the rated horse-power of the turbines installed, but may materially affect the gross and net income.

MATTERS WORTHY OF DETAILED CONSIDERATION

Methods to insure against interruptions, or to lessen the harmful effect of interruptions. In most cases approximately reliable service is imperative. Assurance is impossible and how much less than absolute reliability is imperative depends upon conditions. As Mr. Doherty points out, it is frequently possible not only to tie hydraulic plants together, but also to operate in conjunction with central station plants operated by steam or gas engines. An example of such tieing together is illustrated by the plants described in the *Electrical World* of September 2, 1909, where three water-power plants, a gas-engine plant, and a central station are tied together, and in addition are connected with the plant of a manufacturing company having considerable electric output capacity, normally used for testing electrical apparatus, but which testing can stop in case of emergency.

Equipment to insure against interruptions, or to lessen the harmful effect of interruptions. If steam or other power is to be used for emergencies only, and only for comparatively few hours annually, then the financial cost is the prime consideration, and the hourly expense of operation only a minor factor; but if it is to be used as an auxiliary plant, then the importance of operating expense increases.

Another consideration is the character of labor available. And such reserve plant should be of as simple a character as possible, as in such case it is most likely to be properly handled by the force operating the water powers, and will not require the employment of a high grade stationary engineer.

Penalties for interruptions of service or insurance against interruptions. The prime object of providing a penalty is not to enforce it but rather to make such provisions as to assure the customer that he will receive the service required, which if not received will result in loss to the producer. There is, however, always the danger that by making the penalty too high the producer must materially increase the charge and the customer may pay too high for his insurance. The method described by Mr. Doherty may be applicable to some cases, but I do not understand that he suggests it as a general basis.

Methods of charging. As Mr. Doherty states, there are many methods, but the fundamentally correct one is that the customer should pay:

First, an amount depending upon the maximum demand of the customer at the time of maximum demand on the producer. Unfortunately such basis is not always practicable and the charge must be based on the customers maximum demand.

Second, for the actual energy furnished to the customer.

Whether the maximum demand shall be based on the maximum between certain hours of the day, or whether on the maximum demand whenever it may occur during the 24 hours, and how often it shall be ascertained, will vary with the conditions. The rate at which the actual energy shall be paid for varies with the character of the load curve, including the degree of variableness of the load and the momentary fluctuations. In other words the entire character of the load affects the cost to the producer, and therefore the proper charge to the consumer.

Classes of services which can be advantageously supplied. Mr. Doherty says that "no general and complete rules can be laid down whereby the maximum load-factor can be secured to a hydroelectric company". The writer at this point suggests, as Mr. Doherty does later, that it is not the maximum load-factor which is the important item, but the maximum net income, and that there are cases where a better net income is obtainable from a low load-factor than from a higher one. If, for instance, an existing steam power plant furnishes general supply for a city, and a water power auxiliary is possible, the question will arise whether to increase the capacity of the steam plant or to develop the water power. The probabilities are that the first cost per kilowatt of capacity delivered at the steam power plant will be greater for the water power than for an equivalent addition to the steam plant, but the stand-by losses for such portion of the steam plant as are required to handle peak load may be so great as to more than offset the difference, including interest, maintenance, and depreciation charges. Under such conditions it might be preferable to have the water-power plant take care of the peak load and to operate the steam plant under approximately steady load, or at least an exceptionally good load factor. Under such conditions the load-factor of the water power would be comparatively low. Of course, other things being equal, the better the load-factor, for either steam or water power, the better the net result, but it is seldom that all things are equal.

How to develop the market selected. The points made by Mr. Doherty are, in the writer's opinion, well taken.

How to figure the amount of power which it would pay to develop. This evidently requires a comprehensive study of all the conditions. Under the above heading Mr. Doherty refers to the possible advisability of water power taking the peak load and the inequalities of load when operating in conjunction with a steam plant, and the writer has touched upon this point in connection with a previous sub-heading. It might be well, however, to add that it is important to ascertain at what time of the year the maximum peak will result, and to be sure that there will be water available at such time.

It might also be noted that the amount which can be economically expended for storage capacity can only be ascertained by comparing the estimated result with that obtainable from steam or other power auxiliaries. At the same time consideration should be given to the risk of break-down of transmission lines, and to other features affecting reliabilitiy. The possible benefit of greater reliability cannot be exactly expressed in dollars and cents, but may be a deciding factor, especially when the comparative values otherwise obtained are approximately equal.

Calculations on depreciation. Unfortunately depreciation frequently is not estimated, and the statement is sometimes made by promoters that the appreciation of the property will more than offset the depreciation, and although this may be true, the result, not infrequently, is that money is not available for replacement.

Methods to determine the accuracy of engineers' estimates. Allowing and providing for freedom of discussion and criticism by all the engineers of a corps, or several heads of an engineering force, will frequently disclose errors and also opportunities for betterment, and this can be accomplished without loss of discipline.

P. W. Sothman (by letter): I agree with Mr. Doherty that it is to the best interest of all that projects for the development of water powers should be undertaken and encouraged, which would be in accordance with the movement to conserve our natural resources. These projects should be carried on under one head with well developed plans to insure the greatest possible development of the total energy available from our streams, rather than by numerous interests with no concerted plan of action. With this object in view it is my opinion that governmental control and regulation of all water-power developments would greatly reduce the immense amount of waste power, by bringing under its direction not only one development but all such developments in any territory. It would serve judiciously to carry out plans for uniform supply, thereby assuring the most efficient use of the water powers, including under their control projects for irrigation, forest preservation, storage for the prevention of floods, etc.

It is difficult to estimate the annual earning capacity of the energy wasted in floods, and the direct damage done by them. The proper storing of water will not only permit of development at the site of the dams but will also increase the power of every user down-stream. With well-designed storage systems it would be possible to more than double the horse power available without storage.

The relation of forests to water-power development is of great importance in the uniformity of flow. In Europe large sums of money are spent to forestize large tracts of land and, in recent years, water-power developments have been encouraged and assisted.

It is only by such a system of intelligent government control that advantage can be taken of all the conditions which go to obtain the maximum amount of energy from the available sources.

O. S. Lyford, Jr. (by letter): Engineers are looked upon as experts in money saving, but seldom as authorities on methods of money getting. Market development, contract making, conservation of earnings, and other strictly commercial problems are seldom discussed by this Institute. Most of our attention is given to the creation of facilities for existing enterprises, but in the field of electric railroading, power development, and other public service utilities, as well as occasional industrial enterprises dependent upon electric power or electric processes, the electrical engineer is being called upon more and more to extend the scope of his investigations and include commercial as well as constructive and operative matters. This requires a thorough knowledge of the essential elements of existing business of the kind under consideration, and ability to form a clear conception of the problems affecting the sales, costs, capital charges, net profits, and even the strategy involved in putting the new enterprise in its proper place in the world's business.

In the matter of costs the engineer must be able to foretell, within reasonable limits, not only the construction cost over which he may have more or less control, but the expense of organization, financing, legal work, interest during construction, etc., which are outside of the sphere of engineering. The fundamental question is: " what will be the return on the investment." The " return " is the net profit dependent upon astute management, as well as the potentiality of the market; the " investment " includes all the money spent in getting the enterprise on an earning basis.

One unfortunate feature of this branch of engineering is that there is never money enough in advance of construction to pay for an extended study of the local conditions. The promoter of a new enterprise faces the prospect of losing all the time and money he puts into it, in the event that the construction funds are not underwritten. In consequence, he allows only a few days for engineerng investigations and restricts the expenditure to a nominal sum. The result, as shown in many of the engineering reports presented to financiers, is an insufficient grasp of the essential facts and improper conclusions as to the warrant of the project. The colossal commercial mistakes in water-power developments in the last few years indicate that even the largest enterprises are subject to the risks involved in this lack of digestion of the governing conditions.

It is obvious that the responsibilities involved in engineering of this character require that only engineers with thorough knowledge of the construction and operation of such properties should be employed. This Institute should aid in the development of this knowledge by giving its members the benefit of as much experience of this character as possible.

Referring to the various subjects suggested in Mr. Doherty's paper, the following comments are submitted:

Interruptions and penalties. The striking feature of the plan of "penalties and insurance" is that it starts out with the statement that "the central station company is not desirous of collecting any penalties," and yet the result of what must have been extended negotiations is the most complex and burdensome method of penalizing the power company which has come within the writer's knowledge. The general theory of the scheme looks reasonable at first, but the practical application is a wide departure from the original proposition.

The apparent intent in this case was to obtain insurance by placing heavy financial burdens on the power company. Penalties are not insurance, however, and even these provisions for operation of the steam plant can be only partially successful in limiting the number and duration of the interruptions, because it is necessary to limit the waste involved in the stand-by losses and therefore the length of time that the steam plant is to be held ready for immediate service.

Thus far the only practical way found to positively insure against power house or trunk line interruptions is with storage batteries large enough to instantly take the load. Aside from the lighting and power systems of heavily congested business centers and a few railroad and industrial plants, this extent of insurance has not been found necessary. For all remaining purposes the service which can be given by a well designed and carefully operated prime mover and transmission system has been found adequate and satisfactory. Where a long distance transmission line is introduced between the prime mover and the consumer, the line is the cause of most of the troubles, but the general experience with *first class* installations throughout the country has been that disturbances due to transmission lines decrease in frequency and magnitude as the system becomes adjusted to the local conditions and the operating force becomes skilled in its duties, so that it is commercially practicable to either depend entirely on the distant power house or at best to have available a relay prime mover plant close to the center of distribution, which plant is not held in readiness to fully and immediately relay the transmitted power, but can be prepared for service in a short time. In some instances the load may be divided between the local steam plant and the distant water power plant so that the overload capacity of the steam plant is available as relay for the water power. This works out commercially only when the load is largely in excess of the water power used.

One great difficulty in attempting to protect the power user against the cost of interruption is that penalties cannot in equity be made to apply in the case of strikes, fires and other major catastrophes without a corresponding provision that the power user shall continue to pay for the power in the event of similar casualties in his own business. Therefore, these causes are usually excluded from the penalty provisions, except possibly interruptions due to lightning. Inasmuch as interruptions to the service usually occur more frequently because of accidents beyond the control of the power company than because of negligence or inadequacy, it is at once apparent that penalty provisions do not insure.

The art of generating and transmitting power has now reached a state where a user contemplating the purchase of power may predetermine within reasonable limits what degree of continuity of service may be expected from the plant of the company tendering its power. He should first satisfy himself that the power company has the power to deliver and that its plant is complete, first class and up to date (or will be when his service is inaugurated), and that the operating force is adequate to provide the best service practicable for such a plant. He should next satisfy himself that the service possible with such a plant and organization is such that he can afford to become dependent upon it. Unless these conditions obtain, the deal is impracticable at any price, but if they are found satisfactory, the question of price is next in importance and should be determined by comparison with the cost of alternative methods of obtaining power, taking into account the greater or less reliability. Finally it is proper to introduce into the power agreement such conditions as shall insure that the power company's plant and organization are kept up to the highest practicable state of efficiency. Experience has demonstrated that penalty provisions will have this effect, but simple and moderate penalty provisions have been found adequate. It is not practicable to make up in the penalties for any lack in the inherent possibilities of the power company or for a price that is too high.

The writer has been involved in the making of a number of these power contracts, representing in some instances the purchaser and in others the seller. He has in mind four cases of long-term contracts where the penalty imposed upon the power company is either a fixed sum for each interruption or a provision that the power company shall pay to the consumer for the interruption a sum equivalent to twice that which the producer would have paid during the period of the interruption; or that the power company shall pay the cost of temporary operation of the purchaser's plant during the period of interruption or deficiency. In each case there was more or less difficulty between the two organizations during the first months of operation, but the service of the power company improved until the results had been eminently satisfactory to both parties to the agreement.

The making of a long-term contract is often a matter of weeks or months, because each party is trying to anticipate all the contingencies which may develop during the period of the agreement, and it is well for the engineer not to introduce any complex provisions which can be safely avoided.

Verification of engineers' estimates. It is customary to state in the report of a proposed power development the cost of development per horse power or kilowatt of capacity, and if, for instance, the cost is less than $100 per horse power of generator capacity, or $133 per kilowatt, the general impression is that it is a cheap power. In other words, we have become more or less accustomed to put a measure on the feasibility of the development by determining the unit cost on a capacity basis. This has led to false impressions. The writer suggests two factors for convenience in sizing up these enterprises: One that may be called the "Capacity Unit Cost," which is the cost per unit of capacity above referred to. The other may be called the "Output Unit Cost," which is the first cost per kilowatt-hour of estimated possible annual output *deliverable to the customer* in an average year. The annual output to be assumed for the determination of this factor is the maximum which may be delivered at the customer's premises, as limited by the stream flow, the capacity of the equipment and the efficiency of conversion and transmission, assuming a market sufficient to absorb this maximum.

To illustrate the point, the following table is submitted, giving the cost (estimated or actual) of seven separate water powers in the same general district in our Southeastern states, these powers being developed with heads varying from 30 to 120 feet, and with generator capacity varying from 10,000 to 30,000 kw.

A comparison of plant *D* and plant *E* for instance shows that whereas the first cost per kilowatt of generator capacity is in one case $118.13 and in the other $160.14, the output unit cost (first cost per kilowatt-hour deliverable), for primary power only, is lower with plant *E* than with plant *D*. Therefore, unless a large market for secondary power at a good price can be developed, plant *E* is more feasible commercially than plant *D*, in spite of its larger capacity unit cost.

The capacity unit cost of a proposed development may be made to look low by providing an abnormal amount of equipment, but the output unit cost would thereby be raised and the enterprise be thus handicapped. One factor is a check against the other.

The output unit cost is important as giving an immediate measure of the rate at which the power must be sold to make the enterprise commercially practicable. The project will not be attractive to investors unless it promises, within the near future, net earnings at least equal to 10 per cent of the cash cost of development.

Referring to plant *E* in the following table, the output unit cost is 7.15 cents per kilowatt-hour. The minimum net earnings should be, at least, 10 per cent of this, or 0.715 cents per kilowatt-hour. The cost of operation including labor, supplies, maintenance, insurance and taxes for delivering power to the consumers for plants of the size covered by this table varies between 0.1 and

TABLE I

UNIT COSTS OF HYDROELECTRIC DEVELOPMENTS.

Plant	A	B	C	D	E	F	G
Land and water rights	Cash $14.10	cost $12.86	per $8.89	kilowatt $14.20	of $22.22	generator $13.07	capacity. $15.00
Hydraulic construction (dam, canals, flumes, head gates, etc.)	35.00	43.41	49.50	44.53	51.30	62.42	56.71
Power house building and substructure							
Hydraulic equipment	14.00	13.95	13.00	9.05	7.76	7.84	7.56
Power house electrical equipment	21.00	22.73	19.20	13.85	14.50	13.53	12.50
Transmission line, including right of way	17.20	6.26	18.30	9.00	20.70	17.50	28.50
Substation buildings and equipment	5.72	6.51	9.75	7.55	6.82	8.40	8.40
Distribution system	10.00	6.94	4.58	4.45	15.67	14.58	12.00
Interest during construction	6.30	7.36	5.54	4.75	8.40	6.18	6.16
Engineering	5.90		6.14	6.30	7.00	6.87	6.84
General and legal exp.	3.70		6.20	4.45	5.77	7.48	6.84
Capacity unit cost (total cash cost per generator kilowatt	$132.92	$120.02	$141.10	$118.13	$160.14	$157.87	$160.51
Output unit cost, (first cost per kilowatt hour of annual output deliverable to customer) Primary	0.0825	0.0717	0.0743	0.0815	0.0715	0.1137	0.0985
Primary and secondary	0.058	0.05	0.0625	0.067	No secondary	0.078	0.0820

0.2 cents; say for this case 0.15 cents. The entire output of this plant (all primary in this case) must be disposed of for an average price of 0.715 plus 0.15 or 0.865 cents per kilowatt-hour, or better, to satisfy the investor. If only half the output can be marketed in the near future, the amount of initial development must be diminished or the average price realized must be twice this figure.

In passing, it is suggested that all estimates of cost of hydroelectric projects be subdivided under the general headings of Table I, in order that convenient comparisons can be made. These headings indicate the general groups which vary independently of each other.

Amount of water it will pay to develop. Mr. Doherty makes the rather startling statement that "the operation of a water turbine for 100 hours per year would in some cases warrant its installation." This must be for very unusual conditions and must relate only to a case where the power can be delivered direct from the turbine to the device driven. In the case of electric generation, transmission and distribution, the investment in hydraulic machinery, generators, transformers and transmission copper varies with the peak load, and it has not been found practicable to provide for service of less than six to eight months duration per annum. The possible condition which Mr. Doherty quotes, however, emphasizes the advisability of considering in each case the provision which should be made for extension of plant to take care of short-term power which may later become commercially practicable.

Under this heading, Mr. Doherty makes the statement that "In this character of developemnt (a hydroelectric development having simply a dam from which the water immediately enters the turbine and is immediately discharged to the river below the dam, without any expensive canals, flumes, etc.), all inequalities of load should be taken care of in the hydraulic plant and if it is necessary to run steam, the steam load should be run for such time, and at such uniform rate, as will secure the most economic generation of steam power."

Usually, the lowest annual cost of operation will not be obtained by operating as Mr. Doherty suggests. It will be found that this will result from generating as few kilowatt-hours per annum with coal as practicable. This will mean a high cost of generation from coal per kilowatt-hour, but this is not the principal feature which concerns the stockholder. With combined coal power and water power equipment, the only items of expense which vary materially with the annual output are coal, maintenance and a part of the labor. The variable elements in the two latter items are small and the principal variable is therefore the coal. As a general proposition, then, the operation which requires the least coal per annum will be found the most economical.

Calculations of depreciation. The writer agrees with Mr.

Doherty that practically all the present assumptions for depreciation on hydroelectric plants are too high. These assumptions, however, usually appear only in the preliminary engineering reports. In the reports of actual operation and earnings they are generally noticeable by their absence. A wrong impression of earning power is often made in the early years of operation of a hydroelectric plant by not providing any sum for depreciation in excess of the actual cost of running repairs. In a recent case under consideration the bankers have proposed that the hydroelectric company set aside each year for maintenance and depreciation a sum equivalent to 10 per cent of the gross earnings from operations, the actual cost of running repairs to be paid out of this fund and the balance to be kept in the treasury as reserve for depreciation. There is no direct relation between depreciation and gross earnings, and therefore no absolute consistency in this plan, but if a depreciation fund is built up on this basis, it will insure against misconception of the earning power of the enterprise, and by being inaugurated in the first years of operation, when the apparatus is new and in good order, an adequate fund will be obtained with a much lower burden on the enterprise than would result from the depreciaton rates usually assumed in advance by the engineers reporting such projects.

In this connection "appreciation" should be taken into account as well as depreciation. The probable increase in the cost of steam power and consequently in the market price for water power is sufficient to counterbalance the elements of depreciation known as "inadequacy" and "obsolescence," so that the only element which need be taken into this consideration is the wear and tear, and possible major accidents due to flood, fire, etc.

Government policy relative to water power developments. In view of the widespread interest in this subject, it may be helpful to the members of the Institute to read into this record the substance of an article published in the "Outlook" of December 4, 1909, in which Mr. Gifford Pinchot outlines the "A, B, C of Conservation." This briefly describes what may be taken as the basis of the policy of the Forestry Service under Mr Pinchot.

Answering the question, "Why is it important to protect the water powers?" Mr. Pinchot states in part as follows:

> It is of the first importance to prevent our water powers from passing into private ownership as they have been doing, because the greatest source of power we know is falling water.* * *Under our form of civilization. if a few men ever succeed in controlling the sources of power, they will eventually control all industry as well. If they succeed in controlling all industry, they will necessarily control the country.

Answering the question, "How must it (the protection of the water powers) be done?" He states as follows:

> The essential things that must be done to protect the water powers for the people are few and simple. First, the granting of water powers forever, either on non-navigable or navigable streams, must absolutely

stop. * * * Water powers must and should be developed mainly by private capital and they must be developed under conditions which make investment in them profitable and safe, but neither profit nor safety requires perpetual rights, as many of the best water power men now freely acknowledge. Second, the men to whom the people grant the right to use water power should pay for what they get.* * *There are other ways in which the public control of water powers must be exercised, but these two are the most important.

Answering the question, "Does the same principle apply to navigable streams as to non-navigable?" the following statement is made:

> Every stream is a unit from its source to its mouth, and the people have the same stake in the control of water power in one part of it as in another. Under the constitution, the United States exercises direct control over navigable streams. It exercises control over non-navigable and source streams only through its ownership of the lands through which they pass as in the public domain of National Forests.

Summing up the subject, Mr. Pinchot states:

> It (the conservation idea) asserts that the people have the right and the duty, and that it is their duty no less than their right, to protect themselves against the uncontrolled monopoly of the natural resources which yield the necessaries of life.

It is not my purpose to discuss this policy in detail, but to show how it works out in a practical application.

The practice of the Government based upon the theory quoted is best illustrated in the form of permit which the Forestry Service is willing to issue. The following extracts are taken from a permit issued in April 1909. These extracts indicate the principal restrictions placed upon the power company:

> The gross operation charge for any year shall be calculated by the Forester upon the basis of the quantity of electric energy generated in such year at a maximum rate which shall not exceed the following amounts per thousand kilowatt-hours.

For the 1st year	2 cents
" " 2nd "	4 "
" " 3rd "	6 "
" " 4th "	8 "
" " 5th "	10 "
" " 6th to 10th years inclusive	12½ "
" " 11th " 15th " "	15 "
" " 16th " 20th " "	17½ "
" " 21st " 25th " "	20 "
" " 26th " 30th " "	22½ "
" " 31st " 35th " "	25 "
" " 36th " 40th " "	27½ "
" " 41st " 45th " "	30 "
" " 46th " 50th " "	32½ "

> From the gross operation charges for any year, calculated as aforesaid, deduction shall be made as follows:
>
> (*a*) A sum bearing approximately the same ratio to one-half such gross operation charge as the area of unreserved lands and patented lands on the watershed furnishing the water stored, conducted, and/or used in the works for which permit is hereby applied for bears to the total area of the water shed, as of the beginning of each year;
>
> (*b*) A sum bearing approximately the same ratio to one-half such gross operation charge as the length of the conduit, for which permit is hereby applied for, upon unreserved lands and upon patented lands, over which a right of way for ditches and canals is not reserved by the Act of August

30th, 1890 (26 Stat. 391) bears to the total length of such conduit, as of the beginning of each year;

(*c*) A sum bearing approximately the same ratio to the balance remaining after said deductions "*a*" and "*b*" as the quantity of electric energy generated from water stored artificially by the Permittee, over and above what is generated by the natural flow, bears to all electric energy generated.

The Permittee shall, except when prevented by the Act of God or the public enemy or by unavoidable accidents or contingencies, continuously operate for the generation of electric energy the works to be constructed under the permit hereby applied for, in such manner as to generate after such generation begins, not less than the following percentages of the full hydraulic capacity of the said works measured in kilowatt hours: in the first year 33⅓ per cent, in the second year 40 per cent, in the third year 60 per cent, in the fourth year 75 per cent, in the fifth year 80 per cent, and in every year thereafter 100 per cent.

The permit hereby applied for shall cease and be void upon the expiration of fifty years from the date of approval hereof, but it may then be renewed in the discretion of the duly authorized officer or agent of the United States and upon such conditions as he may in his discretion fix, Provided, That such officer or agent, in fixing such conditions, shall consider the actual value at that time for power and all other purposes of the lands and rights of way within National Forests occupied and used under the permit hereby applied for and the actual value at that time of all improvements lawfully made by the Permittee within National Forests under the permit hereby applied for, but neither the property of the Permittee, if any, outside of National Forests, nor the permit, franchises, bonds, capital stock, or other securities of the Permittee shall be considered in fixing such conditions.

There is also the usual anti-trust clause.

In the project to which this permit applies, the tax, if the drainage area and hydraulic conduit were entirely on forest reserve, and if the entire estimated power were marketed, would amount to about $350 for the first year and $5600 for the 50th year. The estimated annual operating cost of the total output of the plant *including fixed charges* is $180,000. Therefore, in such a case an hydroelectric development entirely on forest reserve would, under these terms, be subjected to a tax of from 0.2 per cent to 3.1 per cent of the total annual operating cost. The charge during the first year is not considerable. Whether the charge for the later years will prove reasonable will depend on the taxes and other burdens which may be imposed on the power company by the State.

The principal burden placed upon the power company under this permit is the 50-year limitation, with no definite assurance that the improvements made by the Company will not in effect be confiscated at the end of the period by refusal to renew.

Mr. Pinchot states "Water powers must and should be developed mainly by private capital and they must be developed under conditions which make investment in them profitable and safe." Referring further to Table I, the figures show that the proportion of first cost chargeable to land and water rights is from 6 to 14 per cent of the total cost of the project. In most of the projects which have come to the writer's attention, the conditions would not warrant a price on the land materially in excess of 10 per cent of the total cost. Therefore, in the case of a power development on Government reserve, in the neighborhood of nine-tenths of the value of the development will be outside of the rights conveyed by the Government. If the present general policy of the Forestry Service is to continue, it is proper that this large proportion of the total cost be protected either by definite provisions for renewals of the license for a similar period or periods, or a provision that the Government may at its option take over the property at an appraised valuation. Without such provisions water powers on Government reserve will not be as attractive as powers on private lands, and it would seem that the general spirit of the conservation idea should result in making the project on the Government reserve the most attractive.

D. S. Jacobus (by letter): The author should be congratulated on preparing a most useful paper, as it is one which deals ably with the subject and at the same time is written with the evident intent of bringing out the ideas of others.

The opinion is advanced that in case a steam plant is used in connection with a water-power plant, as a protection against interruptions, "the internally-fired boiler deserves careful consideration." All available types of apparatus should be considered in the design of a power plant, and the one which is best adapted for the particular conditions should be chosen; in the case at hand, however, the water-tube boiler is so particularly well adapted to the work that, were it not for the desire to bring out discussion, it would seem unnecessary to call special attention to the internally-fired boiler.

In auxiliary steam plants that are held in reserve, all the boilers are not ordinarily kept under steam. The ability to raise steam quickly, starting with cold boilers, is, therefore, an all-important item in this class of work. That there shall be but little stand-by loss in a boiler when held under pressure is also important, and, as the author has pointed out in his paper, this must be considered along with the ability of the boiler to raise steam quickly.

The water-tube boiler is universally acknowledged to be the type which is best adapted for raising steam quickly, and in well-designed boilers of this class the stand-by loss under practical conditions of service will not be greater than that which exists in internally-fired boilers, especially when the water-tube boiler settings are encased in metal to prevent loss due to air leakage. Tests with oil-fuel have shown that with large water-tube boilers the loss from this cause is much less than it is ordinarily supposed to be, as only two per cent of the oil required to run the boilers at their rated power is consumed in maintaining the full steam pressure.

With either coal or oil-fuel and a proper furnace arrangement, steam may be raised, starting with a cold water-tube boiler, up to a pressure of say 200 lb. per square inch in less than half an hour. In fact, in a test where a forced draft was available, and where a coal fire was started with wood on a bare grate, steam was raised to 200 lb. in 12.5 min. after lighting the fire, the temperature of the boiler and the contained water at the start being 72 degrees fahr. If one should attempt to do this with an internally-fired boiler he would surely come to grief, as leakage would result through excessive strains. A water-tube boiler also responds quickly in starting up from a banked fire, especially if a forced blast is available.

In cases where auxiliary steam plants are used to assist in carrying daily peak loads, it may pay to shut down the water power for a portion of the day so as to give the steam plant a more favorable load-curve. There is no better means of storing power than by collecting water behind a dam, and where this can be done it is often best to operate the water wheels at their maximum capacity during the peak loads, and to shut them down during the lighter loads. A way of obtaining continuous service, as pointed out by the author, is to combine a system of several water and steam power plants, and when this is done much can be accomplished in securing economy by making a careful study of the distribution of the load between the stations. The result of experience indicates that auxiliary steam plants in such a system must be run under a load which varies considerably throughout the day, and, furthermore, there is usually a lay-over period of four hours or more when the steam plants are shut down completely. Under these conditions the water-tube boiler is especially applicable, as the fires need not be started up after the lay-over period until a comparatively short time before the engine is started, the number of boilers in service may be reduced to that actually necessary to carry the load as an additional boiler may be quickly cut into the line in case of necessity, and the boilers will readily respond to a high overload capacity.

There is no boiler as flexible in regard to operating conditions as a water-tube boiler, and while it may be run economically at a low rate of evaporation, it may also be run with but little falling off in economy with as high a rate of evaporation as eight or even more pounds of water per hour per square foot of heating surface. In fact, the capacity of a well-designed and properly proportioned water-tube boiler depends simply on the amount of coal that can be burned beneath it, and modern practice is leaning more and more toward running such boilers at high capacities for peak loads, and also for intermittent service of the class herein discussed, because when considered as a whole the economy of the entire plant, including items of capital investment, etc., is better than that secured by running a greater number of boilers at a lower rating.

Ralph D. Mershon (by letter): I quite agree with Mr. Doherty as to the value of water-power securities and as to the probable great increase in their value with the course of time. This increase in value will come about partly through increased fuel cost; partly through the increase in available power of existing plants, due to pondage, as other powers or storage reservoirs are built on the same stream; partly through the institution of new industries which will not install heat-engine power plants and will, therefore, be able to pay a higher price for power than if they already had such power plants; partly through the greater use of off-peak power, either by rearrangement of the hours of operation of industries or by the perfecting of electrochemical processes operative intermittently; and partly through utilization of flood water power by intermittently operative electrochemical processes.

The author speaks of water power being developed under the direction of State and Federal governments and hints even at governmental financial aid to insure full, economic development of the capabilities of streams.

There are few amongst us, I think, in favor of giving to private enterprises absolute title to water power rights on the public domain. If Mr. Doherty had given us a paper devoted entirely to the consideration of the methods and means whereby such aid as that he suggests and hints at could be given without unduly favoring private enterprise, and whereby the ultimate title to water power sites on public domain could be secured to the people as a whole, he would have done a work of much greater value, in my opinion, than he has in this more general and less definite paper, valuable as it is. In fact, the adequate treatment of this one phase of water power development is perhaps more immediately important than that of all the other points he mentions; certainly than that of any one of the other points mentioned.

A carefully worked out scheme which would successfully apply to water powers the suggestion he makes, would apply with little, or obvious, change to other things as well. And one of the greatest problems before this country to-day is to devise schemes which will steer the middle course between socialism and monopoly; schemes which while preserving to the people some proper measure of the unearned increment, will yet allow sufficient profit to the investor to attract capital. I shall revert to this matter later.

Mr. Doherty speaks of the frequency with which estimates have been exceeded and the fact that the blame is usually laid upon the estimating engineer. The estimating engineer is a very convenient scapegoat. It is far from the case that the fault is always his. He estimates under reasonably favorable assumptions, or even under assumptions reasonably unfavorable, but assumes, as he has a perfect right to do, that the construction will be wisely administered. What is the result? The work is often handled either by a number of people in general and no one in particular, or by someone who has achieved fame and fortune running a bank or a pie bakery, and who is, therefore, because of such fame or fortune, assumed to be fully competent to cope with any other enterprise, however widely different from that in which he achieved success; someone who has about as much idea of the proper handling of a power enterprise as the wards of the Prodigal Son had of heaven. The estimates are exceeded and then—it is the fault of the estimating engineer!

In order that such enterprises shall be successful, some *one* must walk the floor with them. And that someone must be something more than a wet-nurse; must be a doctor, or at least know when to call the doctor in, and to call him in time.

Then there is administration by a board of engineers; from which the Lord deliver us! The petty jealousy which will sometimes animate a board of engineers and lead to unwise compromises because of pure stubbornness or vanity, is amazing. I would rather trust my financial fate, if I ever have any, to one man (and to him absolutely) who is honest, has good judgment and the engineering instinct, than the best board of the best engineering specialties every gotten together. He may make some mistakes, who does not?—but what he will save in other directions will much more than pay for any mistakes he is likely to make.

If he has the engineering instinct he will recognize the important and vital problems when they arise. If he is honest he will, if he has the least doubt of the entire adequacy of his own ability to solve them (and even, perhaps, if not in such doubt) call for the services of the best specialists in their solution. If he is wise, he will apply his wisdom in utilizing the findings of these specialists—or in discarding them altogether.

The author speaks of the fact that a good enterprise may go begging because of a conservative prospectus, where a less meritorious one is financed because of the glittering prospects outlined. This condition is not limited to the relation between the financier and the public. It obtains at times as between the financial man and the engineer. And the engineer who promises the greatest returns for the least money and will sign his name to a report setting forth such, will often get engineering work where the man with less imagination (and shall we say with higher ideas of honor?) is passed by. The latter may glean some grains of comfort of a certain sort, later, when the enterprise gets into trouble, but this is poor consolation if a meritorious proposition in which he is interested is rejected because of the distrust bred of the other failure.

This is human nature. If the shoe dealer on one side of the street states honestly just what his shoes will do, and the one on the other side lies about the shoes he sells at the same price, most of us will buy from the man we suspect to be a liar, because we know the honest man's shoes cannot possibly turn out any better than he claims, while there is a chance that the liar will make good.

An engineer's estimate and report should be made in that frame of mind which would obtain if he were going to put his own real money into the enterprise. Indeed, where it is possible, it were well for all concerned, including the engineer, if he had a relatively large "stake" in the enterprise; provided he is not to be crucified by the administration of the pie baker aforesaid.

Mr. Doherty's attitude and, generally, that of those discussing his paper, is, I think, unduly severe on the service from transmission lines. There are hydroelectric transmission plants in existence giving as reliable service as is obtained from steam plants, and there will undoubtedly be more of them as time goes on. Of course an overhead transmission line cannot be made immune to interruption, except at a prohibitive cost. And no matter what expense might be gone to, there would always be the possibility of malicious interference. Generally, whatever can happen will happen, if it has enough chances to happen; which applies to steam central stations as well as to hydroelectric transmission plants.

In the matter of rates, Mr. Doherty seems to be somewhat inconsistent, which inconsistency is partially revealed in his assent to the implied criticism of Mr. Ryerson's remarks anent the sale of off-peak power.

As I see it, there are two ruling propositions implied in Mr. Doherty's remarks on rates; which are as follows:

(1) It is fair that the supplying company should have the full advantage of non-coincidence of peaks; that it should not share this advantage with the consumer.

(2) It is fair to base the charge to the consumer on the cost to him of supplying himself from his own plant.

It seems to me that in the ultimate analysis, the whole thing hinges on (2). For instance, (1) goes to pieces immediately we apply the extreme case of non-coincidence of peaks cited by Mr. Ryerson; that is, the sale of off-peak power. In such case, Mr. Doherty is in favor of dividing some of the advantages with the consumer; and in making concessions in such case, I think it a safe wager he would be guided as to the amount of the concession by what the service would cost from the customer's own plant. I do not advance this as a destructive criticism of Mr. Doherty's well known method of charging, but simply to emphasize the fact that these seemingly fundamentally and inexorably sound schemes of charging are not necessarily so universally sound as they may appear at first sight. And indeed, when so surprising a condition arises as that cited by Mr. Doherty, where the investment and maintenance charges for meters alone exceeds that of the generating equipment to supply them, one is inclined to ask whether in such case it would not usually be better to again throw to the winds the fundamental charging scheme and supply these customers on some flat rate basis; with some cheap device for limiting their maximum demand.

The author regrets the confusion of terms, especially in the minds of the public, and speaks of the desirability of standardizing terms and endeavoring to educate the public to a clearer understanding of their significance. In this I entirely agree with him, though his paper itself is not entirely above criticism in this regard. A large part of the difficulty has arisen from the employment of the term *power* where really *energy* is meant. Usage has made this so universal that it would be hopeless to try to change it now. But strictly speaking, it is no more correct to speak of selling or transmitting power than it is to say that the distance from New York to Chicago is fifty miles per hour.

And it is not the layman only who has confused ideas on this subject. Not long ago, I saw a power contract, drawn by engineers, in which great pains had been taken as to exact expression. It reached the heights of exactness in a paragraph which read about as follows:

> Wherever, herein, the term energy is used, it is meant to signify energy measured in horse power or kilowatts.

Energy in horse power or kilowatts!!!

In his oral reply to the discussion, Mr. Doherty speaks of the practice, so called, of "watering stock." I quite agree with his remarks on the subject. We cannot expect capital to go into enterprises involving a certain amount of risk if the returns therefrom are to be no greater than could be obtained by loaning the same amount of money on security involving a risk much less than that of the enterprise. There must be a profit over and above such returns. I know of no cleaner cut or better way, *provided it is not abused*, of distributing in advance of its realization, the equity in such profit, than by the issue of profit stock. I say *provided it is not abused*, because in the past it undoubtedly has, in some cases, been very much abused by methods savoring of those of the bunco steerer or confidence man. If we could have such laws as would insure the issue at regular intervals of correct, intelligible statements of the results being achieved by corporate enterprises, so that there could be no deception as to the value of the profit stock, the public would at least have the opportunity for independently arriving at a decision as to what this stock was probably worth, and would have some chance for self-protection.

The amount of self-protection possible even under these conditions would depend upon the ability of the public to judge as to the value, or probable value, of the securities. This leads up to another subject, namely that of the ignorance on the part of the public of even the simplest questions of finance. I venture to say that not 10 per cent of the business men of this country, not 10 per cent, even, of the men who are independently conducting business on their own responsibility, could give an intelligent explanation of, for instance, the difference between first mortgage bonds and common stock.

This deficiency is not confined to the public. The engineer, who ought to know something about such matters, is often woefully ignorant. The study of this subject should be made a part of every engineering course, and I am glad to know that some engineering schools are now giving instruction in the rudiments of finance.

In fact, my ideas in connection with this matter go a good deal further. It seems to me it would be well if instruction along these lines were given in every high school, so that the average citizen might have a clearer idea of these matters. I believe that, if he had, he would be much more likely to take an interest in the various creative enterprises arising from time to time (instead of putting his money in a savings bank) thereby acquiring some portion, at least, of his share of the unearned increment; which would result in staving off and modifying, if not forever dissipating, the socialistic influences we are now beginning to feel.

As I have said before, I believe Mr. Doherty could have done us even more good than he has in his paper if, instead of it, he had presented a paper dealing with the possible methods of developing the water powers on the public domain in such a way as would, while attracting capital, secure to the public the titles to them, and at least a portion of the benefits from them. I believe he owes it to himself and this Institute to write such a paper; that there is no more patriotic or philanthropic thing that he could do at the present time.

There are a number of methods which might be devised for arriving at the end suggested. Some occurring to me are as follows:

(1) The water powers might be developed by the Federal or the State governments.

(2) They might be developed by private individuals under the supervision of the Government and with funds supplied by the Government.

(3) They might be developed by private individuals under the supervision of the Government, by the proceeds of bonds guaranteed by the Government.

(4) They might be developed by private enterprise, under the supervision of the Government, with funds raised by the private individuals and with the provision that after a certain period, the Government might take over the property created, at a price either fixed beforehand or to be determined by arbitration.

In no case, however, should they be operated by the Government, but in all cases supervised by the Government to an extent to insure proper maintenance. In the case of (1), (2), and (3), the Government might lease the plants, the lease to be made as the result of bids, contemplating either a compensation to be paid to the Government over and above the interest on the investment, or fixing the price at which power shall be sold, or both. In the case of (4), and perhaps of (3), the operation would presumably be in the first instance in the hands of those constructing the plant, to be open again for competitive bids at the end of the period of such occupancy.

I myself should be rather inclined to some such scheme as (1), (2), or (3), since it would put a premium on brains rather than on money and give an opportunity for men having no capital, but recognized standing as to efficiency and ability, to go in and on their own initiative develop the property and its market, securing a handsome return in the process.

The above suggestions are made merely as tentative suggestions and not even as carefully considered ones. In fact, one of the controlling motives in making them is that they may stimulate the fertile brain of my friend Mr. Doherty, and by arousing his antagonism or otherwise, induce him to write for the High-Tension Transmission Committee the paper I have suggested, and thus lead to more carefully worked out suggestions for arriving at the desired end.

D. B. Rushmore (by letter): The paper presented this evening deals, in an interesting manner, with some of the engineering and commercial features of our power developments, the greater emphasis being laid on the commerical point of view. Some of the statements which have been made this evening concerning the unreliability of electric power transmission in connection with our power developments need modification. While experience has proven that all water powers are not reliable and the disturbances may take place on transmission lines, the troubles which are had are as a rule more or less peculiar to each particular plant. It is doubtful if long-distance power transmission, with the great exposure which comes from the long line traversing unsettled country, can ever be made as reliable as power from a steam station, where the conductors are laid underground, but in certain instances it has been made to very closely approximate this. Of late years the type of construction in both the hydraulic and electrical features has been very much improved over that used in the first hydroelectric developments. The long exposed wooden flume and the wooden pole line have both been replaced by more substantial construction, and in general the factor of insulation has been very much increased.

With regard to the limitations of water power developments, until voltages above 150,000 are reached the financial problem is much more difficult than the engineering one, for with the best of modern engineering transmission lines can be made practically free from troubles.

Supervision of public utilities seems sure to come, and as both engineers and citizens we shall welcome this, but we want it to come in the right way, and in the development and use of our natural resources we have every right to expect the assistance of the Government.

Due to the very large number of features brought up in Mr. Doherty's paper, it is somewhat difficult to discuss as a whole, as it touches on practically all of the important points of hydroelectric developments. Such enterprises are in their very nature almost entirely special, and it is difficult to find any two which have even approximately the same conditions. Where the capacity of the plant is below the minimum stream flow, with or without storage, a steam auxiliary should always be considered, and only the type of hydroelectric plant such as we have at Niagara Falls should be considered as an independent development.

With regard to electrical securities, we have been passing through a period of evolution, and with the formation of larger companies, either as independent growths or as a consolidation of a number of smaller ones, an increased stability is being given to this form of investment. When properly installed and managed there is no form of security which should be more attractive to the general public.

John Martin (by letter): In regard to the relation of water power development to the conservation of our natural resources, I will say that in September this year I read a paper before the Pacific Coast Gas Association, on the subject of the public benefits derived from the development of water power in California. I was particular to mention California, because all of my experience has been in that State, and primarily because our conditions are so different from anything else which exists in the United States. We have wet and dry seasons—sometimes eight months without a drop of rain—and when you consider an engineer must, in order to be wise in his installation, install a capacity not in excess of the minimum flow of the stream, unless he is fortunate enough to find economical water storage, you can understand what difficulties we have to encounter. In all the installations made by our companies we have yet to find the year when we have been short of water for the installations we have made.

The Government in its wisdom, or lack of wisdom, is at this time attempting to make charges for the utilization for power purposes of water on Government lands. Let me tell you that the ownership of the water which the Government wants to charge for in California, is only that of a riparian owner, the same as that of any man who owns land, particularly so where the water for which it wishes to charge is not the water contained in navigable streams, but water which can be stored in reservoirs on land owned by the Government, and these streams pass over the lands in limited quantity, not available for navigation. When that land is disposed of by the Government, its right of control ceases, but it proposes to charge for the use of the water, and thereby conserve (?) the natural resources for the benefit of the people. If it would give the use of that water power free, and would fix a maximum charge for that power, that a company could demand of the people it serves from such development, it would then be conserving some of the rights of the people.

A man securing a water right and wanting to develop a power plant, is like a man who wants a horse and buggy, and first buys the whip. Filing notice of location on a stream gives initial ownership of a water right.

None of the work I have been connected with, aggregating a great many thousands of horse-power developed, is in any way involved with the Government, so I am not speaking from any pique or personal interest.

The greatest difficulty we have encountered in trying to finance our enterprises has been due to the lack of wise installations elsewhere, as a result of greedy capitalists guided by incompetent or dishonest reports from engineers, (who either do not know or would not tell the truth,) and as the result there have been very many financial failures. There is no reason why the man who puts his money into a water plant should not know what the plant is going to cost just as much as the man who has a house to build. We insist on knowing in advance, and having our investments carried out according to some definite scale. We have employed expert independent engineers in the past, but have given them up. Our experiences were with a number of comparatively smaller plants, and not with one large plant.

I take up the part of the paper with regard to compensation for interruption of service. I maintain that no hydroelectric transmission plant can afford to asume an uncertain element of risk of this kind. On the basis of the calculations stated here, in which the first interruption means a penalty of ten days of service, plus one day for each additional minute of interruption. If you have the pole line go out at twelve o'clock at night, and it is not repaired until morning, you would have to run the steam plant for the rest of the year for that interruption, which may not have caused the railway company any inconvenience whatever. The best plan for those who contemplate serving large cities is to depend primarily on the steam plants, as we do, and consider hydroelectric transmission as of fuel value only, or as incidental power.

The question of depreciation is largely a question as to how well you maintain your plant. If you do not take care of the plant properly, the depreciation cost runs very high. This is an individual matter, and, as Mr. Doherty fairly states, every item of construction is a proper charge for amortization or depreciation.

As to the methods of insuring against interruptions, or lessening the harmful effects of interruptions—it may be interesting to you to have me read to you the story of how we handle our power system, over sixteen hundred miles of high voltage lines, by means of a power dispatcher. It will give you some idea as to how we have had to work that matter out, from an operating condition, in a large system covering many miles, with some seventeen or eighteen units.

Mr. Martin then read an article by P. M. Downing, engineer of operation and maintenance of the Pacific Gas and Electric Company on "The Load Dispatching System" of that company, from which the following is an extract:

On the load dispatcher rests the responsibility of keeping the voltage normal and seeing that the fluctuations of load are properly taken care of among the different power houses. To do this requires not only a thorough knowledge of the power house conditions, but a knowledge of the character of the load on the system throughout the day, as this has a decided effect on the regulation of the lines.

A superintendent cannot take out of service a power house, transmission lines, or any other part of the system which would affect the operation of the whole, without first receiving authority to do so from the load dispatcher's office. However, the division of load and regulation of voltage is by no means the most important part of the load dispatcher's duties; that of reestablishing service after an interruption, without unnecessary delay, is a far more difficult problem, and very often calls for quicker and more decisive action. Operating as we do with everything running in together on a common network consisting of approximately sixteen hundred miles of sixty kilovolt lines, trouble on any line will affect the entire system. Then it is that the load dispatcher is busiest. The trouble must be located and the particular section of line on which the trouble occurs must be cut out. The different generating stations may be thrown out of synchronism, or the trouble may even be so severe that the different machines in the power house may be thrown out of synchronism. If the trouble is far enough removed from the station, the generators will not be thrown out, and the interruption is therefore only momentary; nor is trouble on one part of the system always noticed over the entire system. This is taken care of by the system of switching in use, whereby immediately when trouble occurs the different power houses are separated, leaving one or more running together with such lines and load as they can conveniently carry.

An experienced operator can, from the sound of a transformer motor, or regulator, at once tells when trouble occurs. If the station be a switching point, he should be able to handle the switching quickly enough for the trouble to show only as a slight momentary drop in voltage on the unaffected section of line. This condition is possible by reason of the inductance and capacity of the line and would not obtain on shorter lines of higher conductivity.

Immediately after the operation of any high tension switch, either on a direct order from the load dispatcher's office, or during trouble when the regular routine tests are being made, such action is immediately reported to the dispatcher. In this office is located a board showing diagramatically every generating station, transmission line, sub or switching station, also every switch in any of these different stations or on the lines. Stations and lines are represented by being painted on the board, but the switches are represented by dummies which can be adjusted to show the switch open or closed. The particular kind of switch, *i.e.*, whether oil or air, is shown by the shape of the dummy; the oil switches being circular and the air rectangular.

The advantages of a board of this kind will be appreciated when one considers that there are in service on the entire system, approximately one hundred and twenty-five oil and three hundred and fifty air switches, the position of every one of which must be known by the load dispatcher.

Irving E. Brooke (by letter): As a greater number of the possible hydroelectric developments of the United States are taken up, the value of the remaining, as well as the present, developments are increased rather than diminished. The more hydroelectric developments there are constructed, within certain limits, the more readily will their value be recognized, first, by serving as additional means of investment, and, second, by reducing the possible number of developments that can be made. It was only a few years ago that the money interests looked upon water power developments as of very doubtful value, but as numerous examples have proved successful the value of water power securities has been more widely recognized. One point that may be emphasized is that pointed out by the author, that the value of water power development is more likely to increase than is the value of a great many other enterprises, as the cost of coal increases; and until some more economical way of developing energy is found, the value of water power will surely tend to increase. The proper development of water power should be highly encouraged, but enterprises which are unintelligently handled or engineered should be held in check by the state or federal government, the idea being to conserve the water powers until they can be developed in the best possible manner so as to benefit the greatest number.

The possibility of combining water power with irrigation work is one that should be given a great deal of attention at the present time. During the very rapid growth of irrigation enterprises in the West within the past few years it is probable that the chance for power development has been underestimated or even entirely overlooked. Many of these irrigation projects are handled by men familiar only with irrigation developments, who may plan a good irrigation system, but in such a manner as to practically prohibit any future water power development, which development, as well as the irrigation project, might have been designed by one familiar in detail with the requirements of both projects. It is not unusual to see a possible power development greatly handicapped by an irrigation project, or to see an irrigation project almost entirely eliminated by a power development. The possibility of supplying power for pumping water for irrigation purposes is something that required consideration in planning a hydroelectric development in the West. The pumping of water for irrigation can be made to provide a very suitable non-peak load and greatly to improve the load factor of the station.

In considering the development where a combination of irrigation and water power is contemplated the writer has found it convenient to divide the combined developments into two classes, the first being designated as a "direct double-duty development;" the second, "indirect double-duty development." The first term may be applied to a combination irrigation and power development where the water is used first by the hydroelectric plant and then by a gravity system for irrigation; the second, or indirect double-duty development being where the water is used in a hydroelectric development and the power so generated used to pump water for irrigation service. The handicap placed on the direct double-duty development is that the commercial hydroelectric plant requires water at a fairly constant rate for 365 days in the year, while the irrigation requires all of the water necessary during a period of from 100 to 130 days, depending upon the location and length of the irrigation system. Unless the power plant is placed above the storage reservoir, or in case it is placed below where there is a sufficient quantity of water, provision must be made in the former case for letting water pass the hydroelectric plant during the irrigation season, and in either case one project or the other must suffer during some part of the year unless ample storage capacity is provided.

The writer has in mind what might be termed an ideal direct double-duty development; a project where the pipe line leads from the stream to the power house where use is made of the water in the power plant, the water being returned to a natural lake as a storage reservoir below the power house to be used as required for irrigation. However, the natural sites for this ideal development are very few, and in most cases some other provision must be made for taking care of the irrigated lands during the irrigation season.

The author states that a transmission line is the weak point of a hydroelectric development. The reliability of transmission lines is constantly increasing, and as more hydroelectric plants are developed the possibility of any large area or large amount of business depending on any one transmission line is not nearly as great. There is no reason why a transmission line if properly designed and constructed should be considered as great an element of risk as is generally supposed. Proper method of protection from lightning or static disturbances by ground wires, properly designed and tested insulators with protecting rings where severe lightning conditions are encountered, together with anchored or guyed poles at regular intervals along the line, should make a transmission line that will be reliable. The many transmission line failures are in a large measure due to the small consideration that is given this part of the work by the men who are financially responsible for some of our developments.

The writer is familiar with one particular case where the owners were perfectly willing to spend almost any amount of money on the station to secure the most modern and reliable equipment, but were willing to entrust the location and building of the transmission line to one with little or no experience in this work, saying "There is nothing to a transmission line but to set the poles and string the wire".

The fact that complete and thorough investigation of any project is expensive, and that most promoters do not wish to advance a sufficient amount of money for this purpose, usually results in the project being attempted with an incomplete investigation which may mean a poor development or even absolute failure in the end. That all bankers do not follow the rules given by the author is evidenced by the way in which bonds for reliable water power projects are sold.

Where the development company controls and operates the distributing systems, it is evident that no system of penalties need be adopted; in this case the failure to supply continuous and satisfactory service gains its own reward.

In designing a steam plant as an auxiliary to a water power plant, to operate from 40 to 60 days during the year, the first investment in steam plant should be kept as low as possible consistent with obtaining a reliable and serviceable plant. In an installation of this character there are two so-called losses; one is the interest on the investment, and the other is the value of power lost. When these two losses are equal their sum will be a minimum. This means that the interest for one year on the plant investment must equal the value of power lost in the plant from 40 to 60 days. When this condition obtains we have the most economical installation.

In consideration of the above it is usually well to put in a simple steam plant; in some cases even simple engines and tubular boilers may be justified.

The engineer who investigates any proposed project can only estimate what the earning power of such a development will be, based on competent and well-directed management. This is a matter which is often the source of much trouble to the investigating engineer and in many cases is the cause of the development not coming up to the expectation of the owners.

W. G. Chace (by letter): A steam plant which is not run all the time cannot be considered, in any sense, of value in the effort to avoid interruptions of momentary nature or of brief duration. For this purpose nothing but a storage battery can be considered of value, and on account of its large expense it can be maintained with a view of furnishing, during moments of interruptions of service from the hydraulic plant, only those customers to whom such momentary shutdown is serious. The desire to so utilize a battery will naturally affect (1) the choice between alternating current and direct current service as applied to this class of customers, and (2) the number of distribution circuits upon which such a battery can be permitted to float.

The continuous use of steam plant in connection with a service supplied from hydroelectric source and where the supply of water is sufficient for all hours of the day and all seasons of the year, is, generally speaking, inexcusable; and its chief reason for existence is the fact that it may have been in the service prior to the construction of the hydraulic plant. When the hydraulic plant shall have been loaded so as to be taxed to its limit for the winter peak, there remains to the management in many instances the choice between putting in new steam plant, and building a second hydraulic plant, and this choice will not be governed by the variation of cost of the kilowatt-hour at different hours of a given day, as referred to in the discussion by Mr. Stott, but will be governed by the relative magnitude of all charges for the year of operation; because, although usually the income is based on the rate charged by the company per kilowatt-hour and although frequently the cost per kilowatt-hour throughout a considerable portion of the day may be found lower with the steam plant than with the hydraulic plant, still it is not the relative cost of such a unit of energy, but the relative cost of the year's operation, which should serve as the basis of choice in this contingency.

A recent experience of a large company, whose hydraulic plant was shut down completely for two days and partially thereafter limited in output for six weeks, developed the fact that the steam station owned by the company, and of capacity nominally 40 per cent that of the hydraulic plant, and which had served the company up to a period of three years prior to the accident, could not be depended upon for anything like its nominal output in the emergency; and the effort to operate it developed such a series of difficulties due to the long period of idleness and to the consequent lack of attention (and perhaps reasonable lack of attention), that but a very limited portion of the load could be carried by it. With expensive fuel and labor and with a proven hydraulic plant, the owners had not considered themselves warranted in expending large sums upon the maintenance and necessary regular operation of the steam plant, required to keep it in condition. That this is a common feeling in the presence of a dependable hydroelectric development and high tension transmission, is supported by the statements of Mr. Barton concerning the Buffalo steam plants on the advent of Niagara power.

The best insurance available in a given area is that contingent upon the existence of two hydroelectric plants of similar frequency and capacity, whether they be operated by the same owner or in competition. With such plants there is much less need of expensive stand-by equipment than there is in isolated steam plants, each of which would necessarily carry a considerable proportion of spare capacity; and, moreover, so long as the water power is not completely developed, the costs of hydroelectric stand-by in the shape of spare units is less than that of steam stand-by in a separate station fully equipped with labor and carrying a considerable investment in fuel.

Depreciation. There can be no question but that the proper annual charges for depreciation in a well maintained hydroelectric plant are relatively small figures. It may be interesting to set forth here some facts concerning a large hydroelectric plant with whose construction the writer has had connection. Table I sets forth the distribution of the gross cost of this development, the figures being given in percentages. The equipment now being installed has a rated generator output of 15,000 kw. and the excavations and permanent structures are designed, and are being built for an ultimate rated equipment of 45,000 kw. From this table it will be noted, incidentally, how moderate is the cost per unit of the capacity to be added after the completion of the original construction, a triplication of capacity being obtained with an addition of only 80 per cent to the original investment, all calculations on this subject being based upon the construction and equipment contracts let during the period of 1909–1910.

TABLE I

	15,000 kw.		30,000 kw.		45,000 kw.
	Per cent initial cost	Per cent ultimate cost	Per cent total cost	Per cent ultimate cost	Per cent ultimate cost
A. Real estate, preliminary expenses, excavations, cofferdams and engineering	22.5	12.63	19.1	14.50	16.35
B. 25 miles of standard-gauge railway with two river crossings	14.6	8.05	11.5	8.70	9.78
C. Permanent structures consisting of dams, weirs and buildings	24.9	13.76	21.7	16.47	22.27
D. Equipment of power house and terminal station, including transforming and control apparatus for 66,000 volts	22.7	12.50	29.1	22.08	35.30
E. Transmission and telephone line structures	15.3	8.41	18.6	14.13	16.30
	100.00	55.35	100.0	75.88	100.00

The proper charge for depreciation is a relative one and depends upon the class of construction, on the nature of the design, on the character of the attendance, on the amounts of money expended for maintenance and on conditions of climate and surroundings. Then again, a property cannot depreciate to a value less than that which it possesses as scrap, and although this item is generally omitted from such discussion, it is worthy of consideration. Mr. W. R. Cooper, in discussing a paper read by Mr. Robert Hammond before the Institution of Electrical Engineers, April 25, 1907, gives a table of the probable life of the various elements of the power plant and of the probable scrap value at the end of the period. On some of the elements of a hydroelectric plant the market price at the date of purchase enters largely into the scrap value which may be assumed, and this applies most particularly to the copper, purchase of which in the shape of conductors during recent years has varied in Canada from fifteen cents to twenty-eight cents per pound, so that a scrap value of ten cents per pound, which is not unreasonable at any time and which is unreasonably low under certain market conditions, will vary from 66 per cent to 53 per cent of the original costs, and the possible proportion of depreciation during the life of the transmission line may range from 34 to 47 per cent under the above mentioned conditions of market, and may even be zero or a negative quantity if purchase be made at the lowest price mentioned and the property be scrapped under conditions of a much higher price of copper.

It is interesting to note that our friends the salesmen for the aluminum companies claim that their principals can get more for aluminum in almost any other form than in that of electric conductors, although doubting Thomases may point out that these same gentlemen are particularly anxious to sell aluminum for electric purposes.

The same argument regarding scrap value applies to all machinery as well as to the conductors. It may be generally remarked that it is not reasonable, in view of the broad assumptions as to the life of the various portions of the equipment, to carry the calculations for depreciation to many significant figures. If this item were called by the name of "Renewal Fund" it might appear a much more necessary element than the accountants of some of the operating companies now seem to consider it.

Table II sets forth a calculation of the charges for depreciation which would be reasonable for the plant referred to in Table I. Ability on the part of the owner to borrow money at very low rates permitted extremely substantial constructions at the present date, so that the depreciation and maintenance charges thereon can be safely estimated very low.

TABLE II
SCHEDULE OF DEPRECIATION CHARGES ON PLANT REFERRED TO IN TABLE I

A	*B*	*C*	*D*	*E*	Interest 4½ per cent ultimate period 50 yrs.
22	15	25	23	15	Per cent of total cost.
50	30	50	25	30	Life—years.
100	2	0	10	20	Final scrap value—per cent original cost.
0	98	100	90	80	Value disappearing—per cent original cost.
0	1.64	0.56	2.26	1.64	Rate depreciation—per cent.
0	0.24	0.14	0.47	0.20	Annual depreciation—per cent original cost.

Total annual depreciation 1.05 per cent of gross original cost.
Of this depreciation the groups contribute respectively the following percentages:

A	*B*	*C*	*D*	*E*
0	22.8	13.3	44.8	19.1

This table is self explanatory.

It is interesting to note that the annual charge, namely, 1.05 per cent of the gross original cost, is practically identical with that given in Table II in the discussion by Dr. Hutchinson. It is also interesting to note that item *B*, the construction railroad, which it was necessary to build for this plant, demands 22.8 per cent of the entire annual charge for depreciation.

The item called "Obsolescence" should not, in general, be calculated upon elements of the installation other than equipment, and it is a mistake to make such a charge on the basis of the cost of the entire plant. With 4½ per cent money, Dr. Hutchinson's allowance for this item in connection with a steam plant, 6 per cent, corresponds to a life of thirteen years only, and would seem unreasonably large even as applied to the equipment alone, though it might have been reasonable fifteen years ago. His corresponding charge for the hydraulic plant corresponds to a life of thirty-two years and can surely not be accepted, even as applied to the equipment alone when we consider that in very many installations now being constructed the individual unit is designed of the largest size which is consistent when matters of speed, cost, ultimate capacity of water power, water velocities and dimensions of market are kept in mind, and when the present very high efficiency obtained on both the electric and the hydraulic ends of the machinery is considered. In fact, it is hardly comprehensible that any charge for obsolescence should be allowed or required in a conservative engineering estimate of the cost of the energy to be delivered from a hydroelectric plant.

In this connection the word "obsolescence" has not the same meaning as it had twenty years ago when the gas engine, the alternating current machine, the steam turbine, and even the modern steam reciprocating engine, to say nothing of the steam boilers now available, were yet things of the future; and it has even less meaning than it had fifty years ago when the practical applications of the various elementary principles of nature, such as heat, magnetism and electricity were in their infancy; in other words, we have now at our command mechanical applications of most of the known principles of energy and the prospects of future radical advances are, to that extent, limited.

Moreover, the idea of obsolescence as advanced in the discussion by Dr. Hutchinson, where he refers particularly to the New York Edison Waterside Station No. 1, relates particularly to land values, and it cannot be that there is much prospect of the early shutting down of this station by reason of obsolescence of the equipment as such.

In General. The writer is of the opinion that electrical engineers, a majority of whose experience is gained in connection with steam electric stations, often have erroneous ideas of the overload capacity which can be reasonably counted upon in hydroelectric plants carefully designed. Modern reaction turbine practice has established comparatively high efficiency above one-half load, and in so far as water economies are concerned the point of maximum efficiency being about three-quarter gate opening, it is reasonable to choose turbines whose ultimate capacity is from 25 per cent to 40 per cent beyond the rated capacity of the direct connected electric generators. Then, too, no plant should be designed for operation with fewer than four generating units so that a very reasonable degree of insurance against shutdown and, ipso facto, overload capacity, would exist at all hours of the day.

The plant to which the Tables I and II apply consists of units made up of generators of 3,000 kw. rated capacity, direct connected to twin turbines, on horizontal shaft, of 5,200-h.p. ultimate capacity.

With steam stations of less than 5,000-h.p. capacity and with coal costing from $4.00 to $7.00 per ton, as is quite common in many of our centers of distribution, steam-electric power cannot be generated as cheaply as is claimed by Dr. Hutchinson.

In the matter of maintenance—Mr. Barton's statements are most interesting as applied to stations of the Niagara type. As to the costs of maintenance of the electrical equipment, these can be considered fairly representative; but as to the 2 per cent cost of maintenance of the hydraulic equipment it must be borne in mind that all of these generating units are of the vertical type with shafts approximately 120 feet long, with elaborate and complicated thrust bearing mechanism, including auxiliaries, and are in all much more bulky than the hydraulic equipment of horizontal shaft outfits as ordinarily designed, even for heads as great as those existing at Niagara Falls; so that if 2 per cent is a proven figure for this type of equipment, it would be fairly safe to estimate that for a horizontal equipment up to, say, 50 ft. of operating head such maintenance should not exceed 1 per cent per annum and but slightly greater than 1 per cent for plants with heads higher than 50 ft.

As to Mr. Doherty's conclusions, the writer is of the opinion that items 3, 4, 5 and 7 are subjects to which the Institute might well turn its attention for a few months. It is unfortunate that work along the lines of item 3 should have been so much neglected. Consulting engineers find it extremely difficult to obtain enough or reliable data concerning the streams whose water falls they are called upon to consider. The work done recently in Wisconsin is typical of what should be carried out under Government care throughout the whole of America, and especially it is desirable that these studies be undertaken in connection with the efforts of both Canada and United States to conserve their forests and other resources. In Ontario, the first Hydroelectric Power Commission issued, in 1906, a file of five papers covering the streams south of the "height of land," that is, within the now populated area, and though upon this work not enough of moneys have been expended, nor, unfortunately, has a systematic series of river studies been inaugurated, still it is an indication of what can be done at moderate expense, and it is typical of the kind of information which should be accessible concerning all water powers whose location makes them of early value.

A paper presented at a meeting of the Toronto Section of the American Institute of Electrical Engineers, Toronto, Ont. December 18, 1908.

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NOTES ON THE COST OF POWER.[*]

BY H. G. STOTT.

In engineering estimates there is probably no item which contains so many variables as that representing the cost of power. Consequently we frequently find a wide divergence of opinion as to the results which may be expected under different conditions. In all types of plants the influence of investment upon the cost of power is one which is apt to be slighted in the estimates, and if not slighted it seems to be subject to more errors than any other factor which enters into this cost. This is particularly the case with hydraulic plants, as of necessity water storage, flumes, racks, tail-race, etc., enter into the estimate, with the result that the actual cost has sometimes been found to be 100 per cent greater than the estimated cost.

In the same way indeterminate items of cost, such as foundations, cost of labor, etc. enter into practically all the calculations, so that when we take into consideration the influence of location upon the cost of coal, labor and water, as well as upon the investment, it is readily seen that the actual cost of power is of necessity so variable as to make impossible anything like a standard cost per kilowatt-hour.

With the above limitations in mind, the following notes on the cost of power have been compiled with the idea that they might form a guide to show at least the fundamental relations between the various items going to make up the cost of power, and at the same time show what is actually being done to-day in large plants having a maximum load of over 30,000 kw.

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[*] The author wishes to acknowledge the work of Messrs. G. I. Rhodes and R. J. S. Pigott in calculating and plotting curves, and the kindness of the New York Edison Co. and Interborough Rapid Transit Co. in furnishing load-curves.

The following table has been taken from a paper* contributed by the author two years ago and has been expanded and revised so as to bring it up to the results now obtained in actual practice. The principal changes made have been due to the better economy obtained in the steam turbine, and in the reduction of the total fixed charges from 12 per cent to 11 per cent; fixed charges composed of 5 per cent interest, 1 per cent taxes and general administrative expenses, and 5 per cent for amortization or obsolescence in the steam and hydraulic plants.

RELATIVE COSTS PER KILOWATT-HOUR. DISTRIBUTION OF MAINTENANCE AND OPERATION

	Reciprocating steam plant	Steam turbine plant	Reciprocating engines and low-pressure steam turbines	Gas-engine plant	Gas engines and steam turbines	Hydraulic
MAINTENANCE						
1. Engine room, mechanical.......	2.59	0.51	1.55	5.18	2.84	0.51
2. Boiler or producer room........	4.65	4.33	3.55	1.16	1.97	....
3. Coal and ash-handling apparatus	0.58	0.54	0.44	0.29	0.29	....
4. Electrical apparatus...........	1.13	1.13	1.13	1.13	1.13	1.13
OPERATION						
5. Coal........................	61.70	55.53	52.44	26.52	25.97	....
6. Water.......................	7.20	0.65	0.61	3.60	2.16	....
7. Engine room, labor............	6.75	1.36	4.06	6.76	4.06	1.36
8. Boiler or producer room labor..	7.20	6.74	5.50	1.81	3.05	....
9. Coal and ash-handling labor....	2.28	2.13	1.75	1.14	1.14	....
10. Ash removal..................	1.07	0.95	0.81	0.54	0.54	....
11. Electrical labor..............	2.54	2.54	2.54	2.54	2.54	2.54
12. Engine room lubrication........	1.78	0.35	1.02	1.80	1.07	0.20
13. Engine room waste, etc........	0.30	0.30	0.30	0.30	0.30	0.20
14. Boiler room lubrication, etc....	0.17	0.17	0.17	0.17	0.17	....
Relative operating cost per cent....	100.00	77.23	75.87	52.94	47.23	5.94
Relative investment per cent.......	100.00	75.00	80.00	110.00	96.20	100.00
Probable average cost per kilowatt.	125.00	93.75	100.00	137.50	120.00	125.00
Probable fixed charges............	11%	11%	11%	12%	11.5%	11%

For steam-turbine plants larger than 60,000 kw. the cost per kilowatt may be reduced to $75.00.

In the other items will be found changes due to the reduced cost of steam turbines, and also due to the possibility of saving the water of condensation by separating out the oil between the reciprocating engine and the steam turbine. Under the

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* Power Plant Economics, by Henry G. Stott. Transactions A.I.E.E., 1906. Vol. xxv. pp. 1–27.

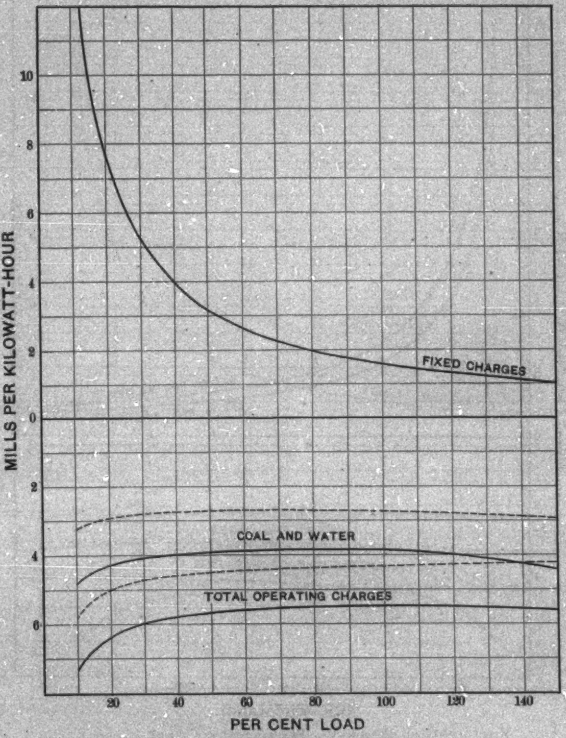

FIG. 1.—Cost of power. Reciprocating steam-plant.
Plant cost = $125 per kilowatt.
Interest, taxes, depreciation, etc. = 11%.
Solid lines = coal @ $3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

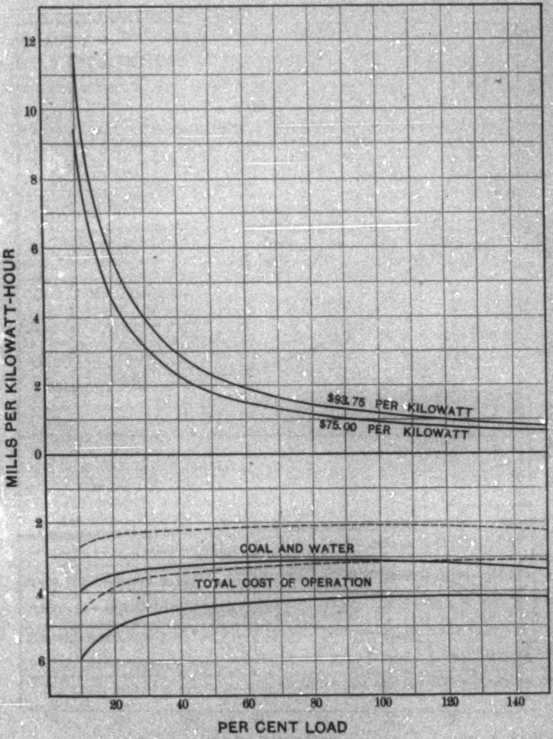

Fig. 2.—Cost of power. Steam-turbine plant.
Plant cost. = $93.75 per kilowatt —A.
Plant cost = $75.00 per kilowatt—B.
Interest, taxes, depreciation, etc. = 11%.
Solid lines = coal @ $3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

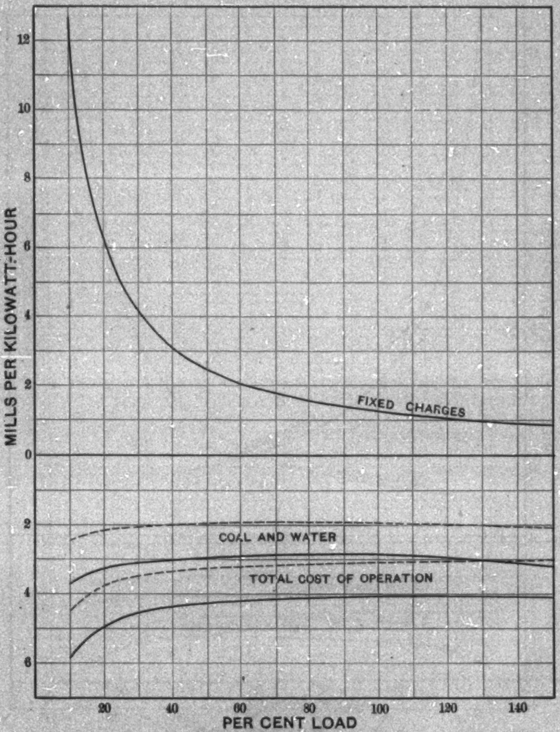

Fig. 3.—Cost of power. Reciprocating engine and low-pressure turbine plant.

Plant cost = $100 per kilowatt.
Interest, taxes, depreciation, etc. = 11%.
Solid lines = coal @ $3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

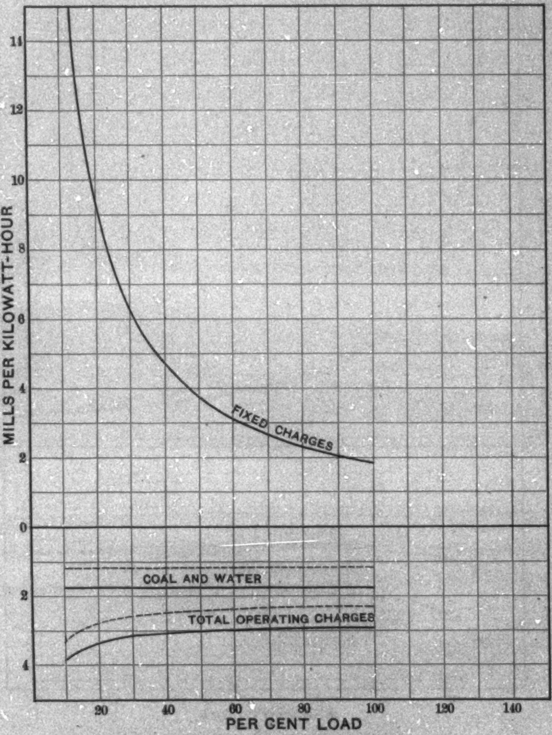

FIG. 4.—Cost of power. Gas-engine plant.
Plant cost = $137.50 per kilowatt.
Interest, taxes, depreciation, etc. = 12%.
Solid lines = coal @ $3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

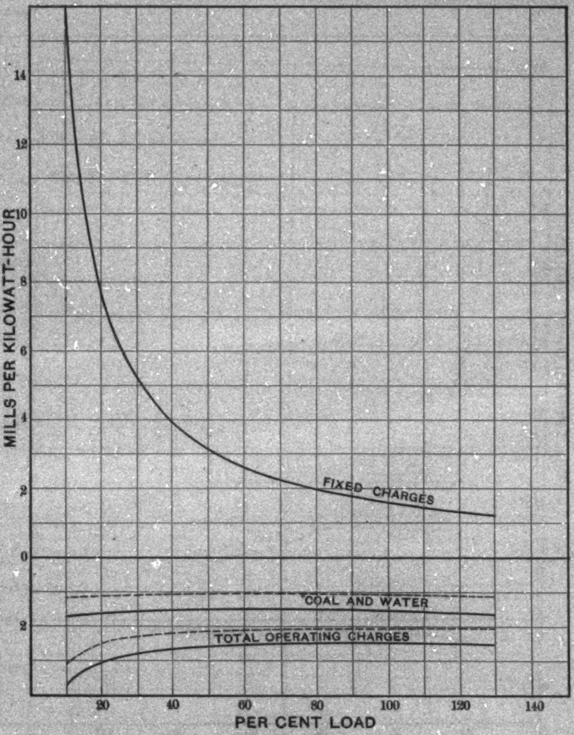

FIG. 5.—Cost of power. Gas-engine and steam-turbine plant.
Plant cost = $120 per kilowatt.
Interest, taxes, depreciation, etc. = 11.5%.
Solid lines = coal @$3.00—14,500 B.t.u. per lb.
Dotted lines = coal @ $1.50—11,000 B.t.u. per lb.

heading of *Coal*, in the reciprocating engine and steam turbine plant, it will be found that this amount has been increased so as to cover the difference between the theoretical amount which had to be assumed in 1906, and the actual amount guaranteed by the manufacturer in 1909.

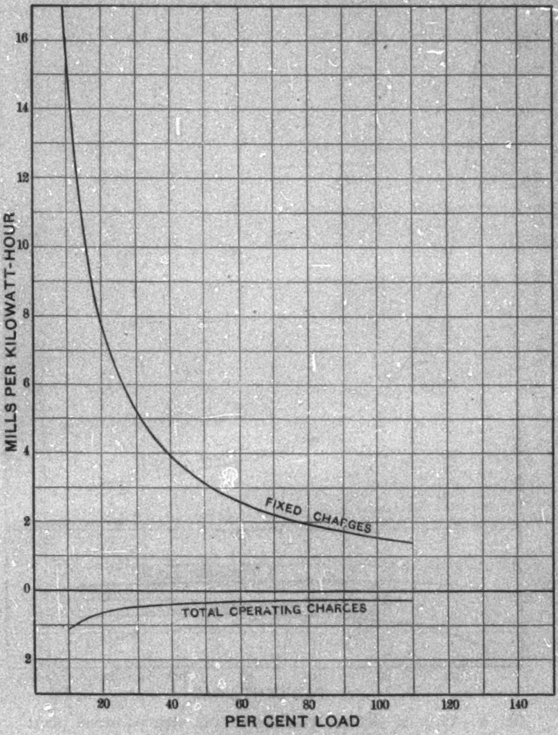

FIG. 6.—Cost of power. Hydraulic plant.
Plant cost = $125 per kilowatt.
Interest, taxes, depreciation, etc. = 11%.

In the accompanying curves, the cost of delivered coal has been assumed at $3.00 per ton for a high-grade coal having 14,500 B.t.u. per lb. and also at $1.50 per ton for a low-grade coal having 11,000 B.t.u. per lb. so as to illustrate the effect upon the cost of power.

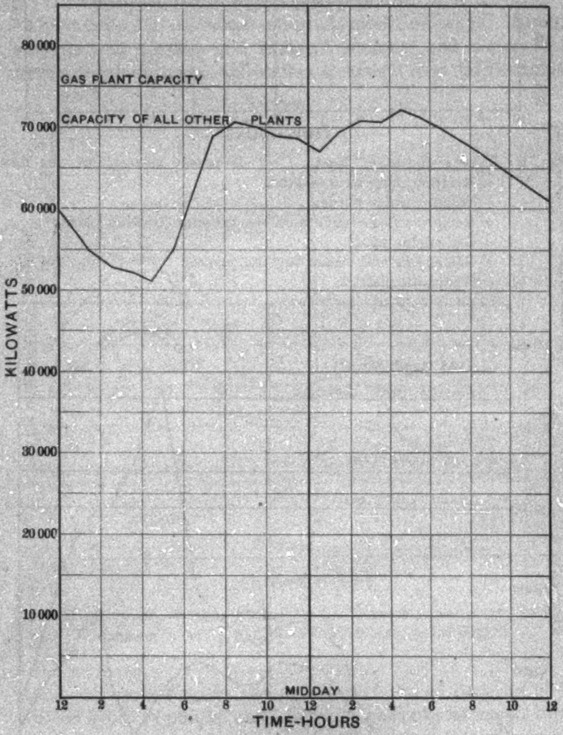

Fig. 7.—Typical industrial load.

Figs. 1 to 6 inclusive show, with various types of plants, the fixed charges upon the upper curve and the operating charges below the axis, so that the sum of the ordinates gives the total cost per kilowatt-hour for any load-factor on the plant. It will be

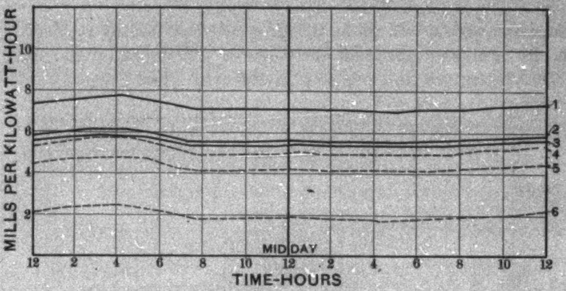

FIG. 8.—Typical industrial load. Cost of power throughout the day.

1. = Reciprocating steam-plant.
2. = Steam-turbine plant.
3. = Reciprocating-engine and low-pressure turbine plant.
4. = Gas-engine plant.
5. = Gas-engine and steam-turbine plant.
6. = Hydraulic plant.

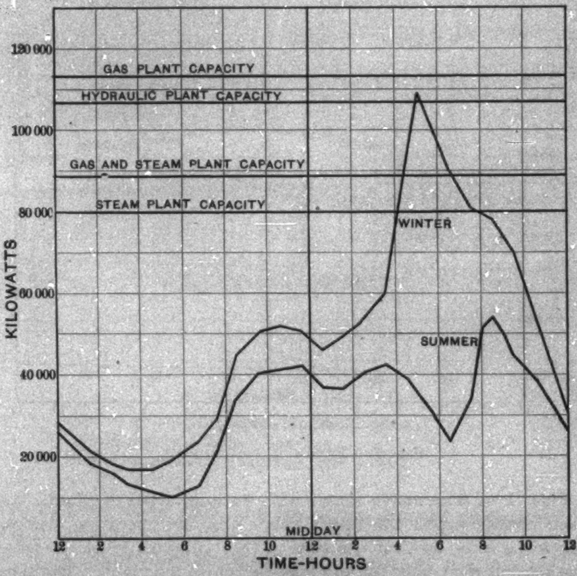

FIG. 9.—Typical lighting load.

noted that all the steam plants are assumed to have 50 per cent overload capacity, sufficient to carry them over a peak-load of two hours, whilst the gas plant has no overload capacity. The combined gas-engine and steam-turbine plant has 25 per cent and the hydraulic plant 10 per cent overload capacity.

Figs. 7 to 14 inclusive show typical industrial, lighting, (summer and winter) and railroad (summer and winter) load-curves. On these curves will be found straight lines drawn through points corresponding to the necessary installed capacity of the various types of plants, and a second series of cost curves bringing out in a very suggestive manner the cost of furnishing power at every hour of the day. As an illustration, refer to Fig. 11, which shows the cost of power on a summer lighting load.

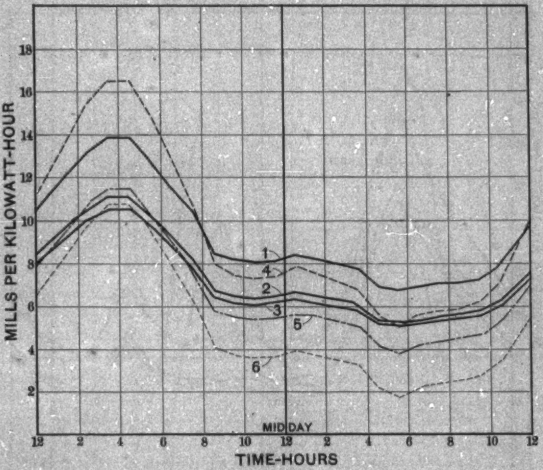

Fig. 10.—Typical winter lighting load. Cost of power throughout the day. Curves, 1 2, 3, 4, 5, and 6 same as in Fig. 8.

During the greater part of the day, No. 4, or the gas-engine plant, is the most expensive, owing to the necessarily high fixed charges. For the same reason, the reciprocating steam-engine plant is also high.

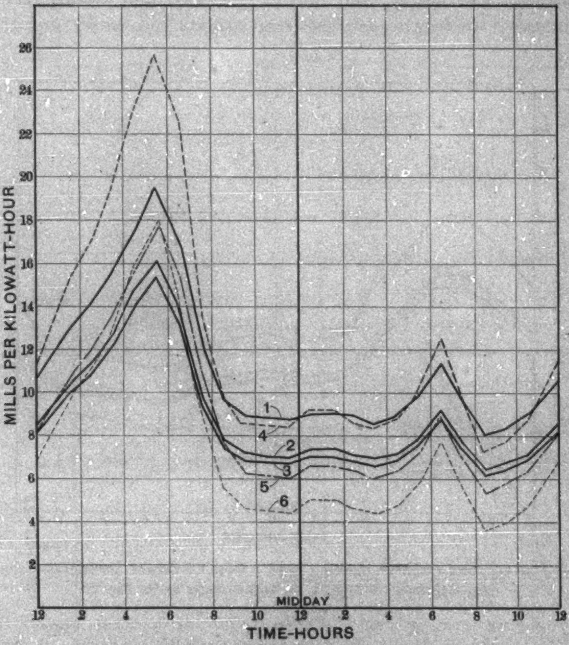

FIG. 11.—Typical summer lighting load. Cost of power throughout the day. Curves 1, 2, 3, 4, 5, and 6 same as Fig. 8.

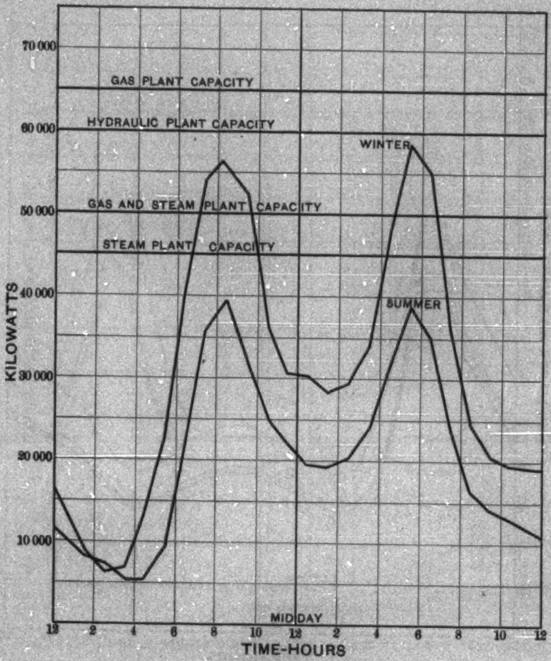

FIG. 12.—Typical railway load.

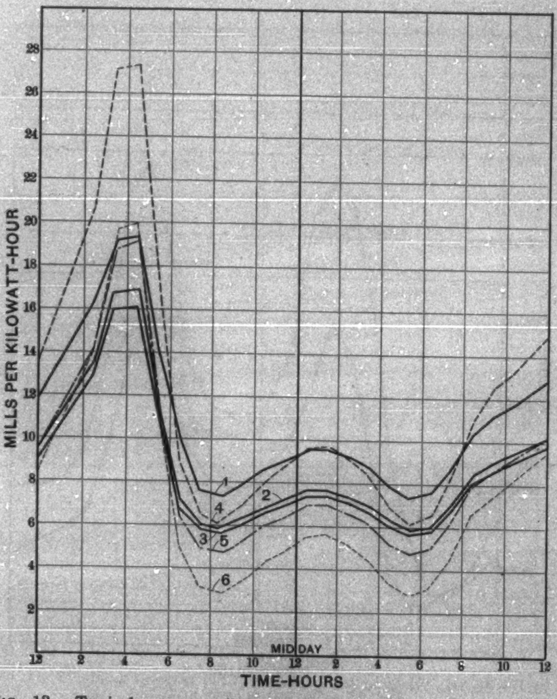

FIG. 13.—Typical summer railway load. Cost of power throughout the day. Curves 1, 2, 3, 4, 5 and 6 same as in Fig. 8.

During the light morning load the hydraulic plant is also handicapped by the fixed charges, but the low operating costs render it the most efficient upon the whole.

Fig. 5, representing the plant in which one-half the installed capacity consists of gas engines and the other half of steam turbines, makes so excellent a showing on all the load-diagrams that we may expect to hear more of this type of plant in the future.

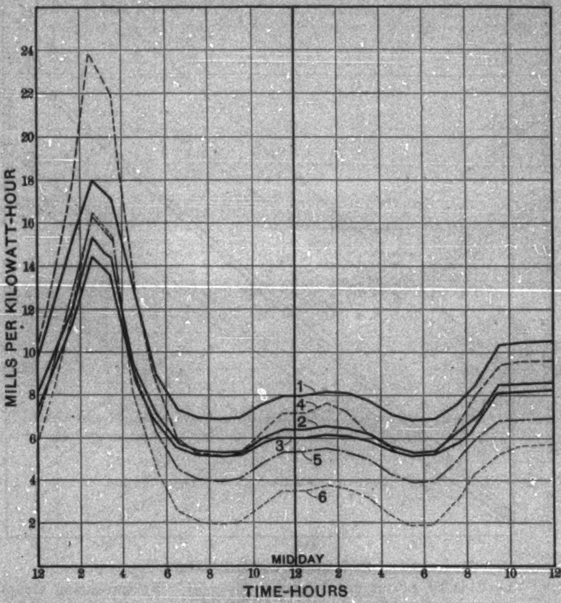

Fig. 14.—Typical winter railway load. Cost of power throughout the day. Curves 1, 2, 3, 4, 5, and 6 same as in Fig. 8.

In all these comparisons it must be remembered that the costs are worked out to the generating plant *bus-bars only*. In practically all cases, therefore, the costs discriminate in favor of

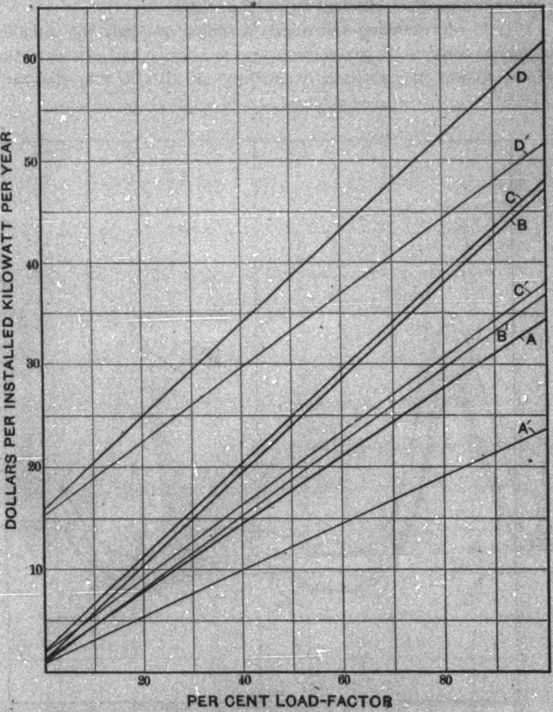

FIG. 15.—Cost of power per kilowatt per year. Reciprocating steam-plant.

Plant cost $125 per kilowatt.
Fixed charges = 11%.
A, B, C, D = coal @ $3.00—14,500 B.t.u. per lb.
A′, B′, C′, D′ = coal @ $1.50—11,000 B.t.u. per lb.
A = Coal and water.
B = A + Mechanical maintenance and operation.
C = B + Electrical maintenance and operation.
D = C + Fixed charges.

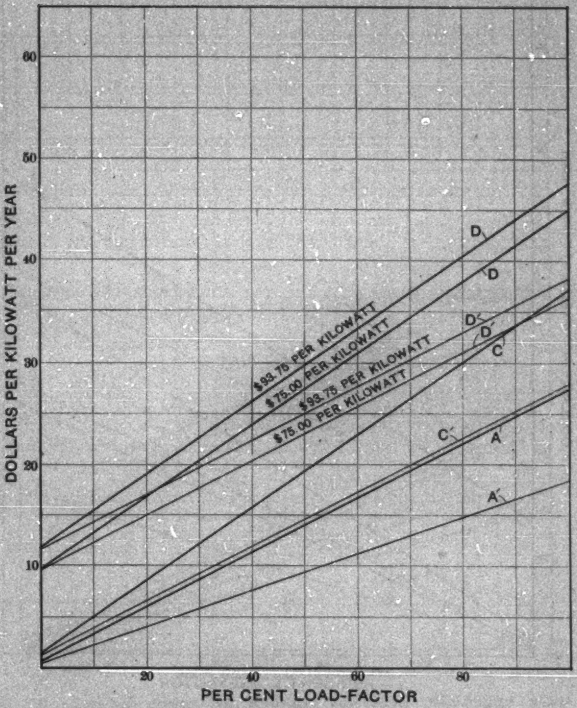

FIG. 16.—Cost of power per kilowatt per year. Steam-turbine plant. Plant cost $93.75 and $75 per kilowatt.
Fixed charges, 11%.
A, B, C, and D same as in Fig. 15 = coal @ $3.00—14,000 B.t.u. per lb.
A', B', C' and D' " " " " " = coal @ $1.50—11,000 B.t.u. per lb.

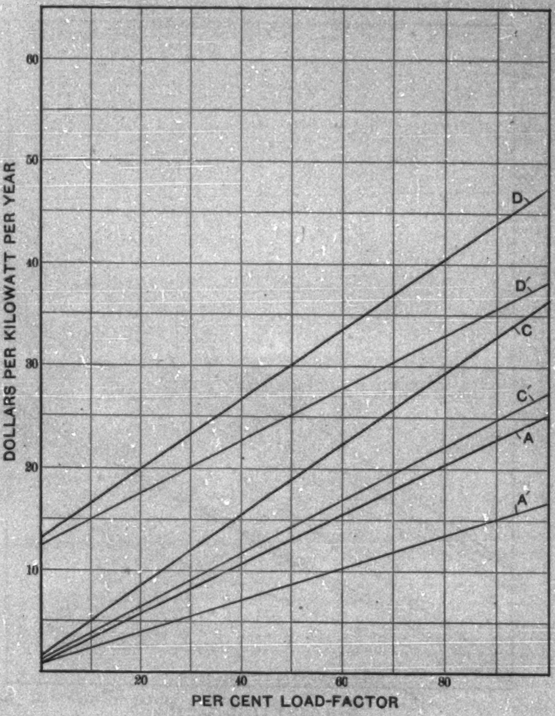

Fig. 17.—Cost of power per kilowatt per year. Reciprocating-engine and low-pressure turbine plant.

Plant cost $100 per kilowatt.
Fixed charges 11%.
A, B, C, D
A′, B′, C′, D′ } same as Fig. 15.

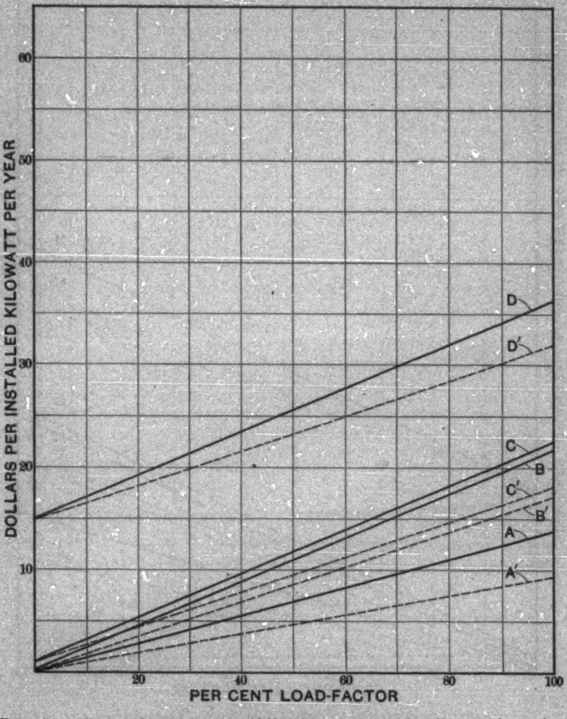

FIG. 18.—Cost of power per kilowatt per year. Gas-engine plant.
Plant cost = $137.50 per kilowatt.
Fixed charges 12%.
Solid lines, Dotted lines, A, B, C, D } same as Fig. 15.

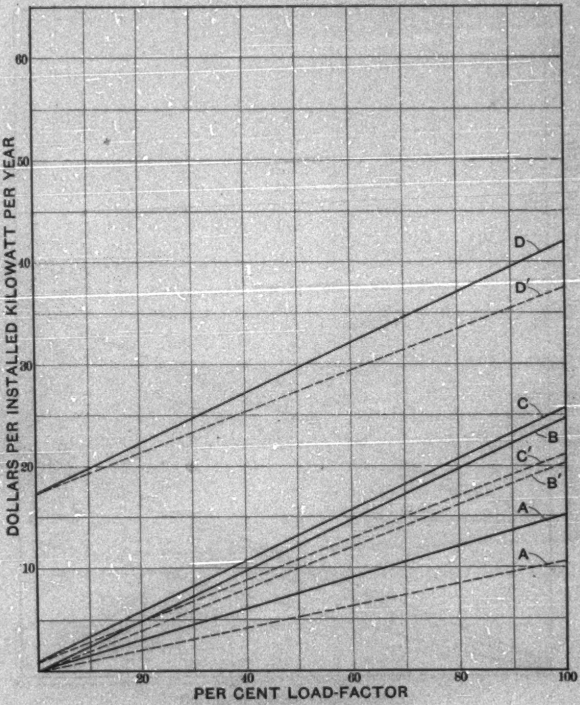

Fig 19.—Cost of power per kilowatt per year. Gas-engine and steam-turbine plant.

Plant cost = $120 per kilowatt.
Fixed charges 11.5% per annum.
Solid lines
Dotted lines
A, B, C D
} same as in Fig. 15.

the hydraulic plant, which almost invariably has to assume as a part of its expenses, the fixed charges and operating expenses of the transmission lines. Obviously, it was inadvisable to bring such an unknown quantity into this comparison; but the fixed charges and operating expenses of a long-distance transmission line connecting to an hydraulic plant may be sufficient

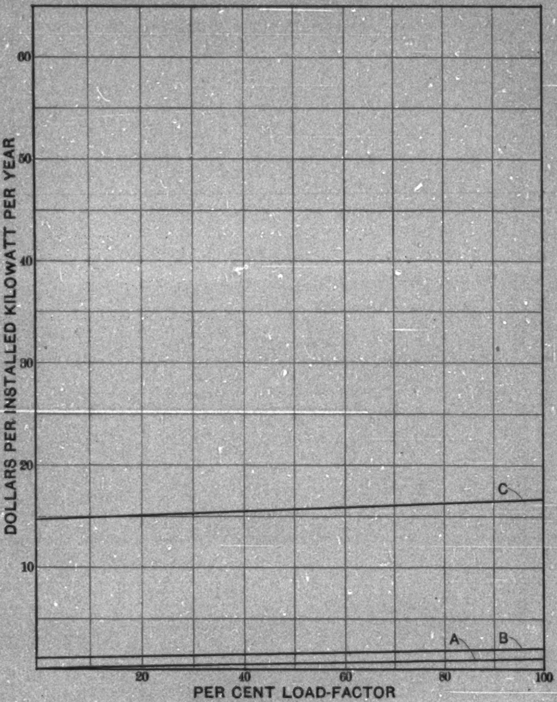

Fig. 20.—Cost of power per kilowatt per year. Hydraulic plant.
Plant cost = $125 per kilowatt.
Fixed charges 11% per anum.
A = Mechanical maintenance and operation.
B = A + Electrical " "
C = B + Fixed charges.

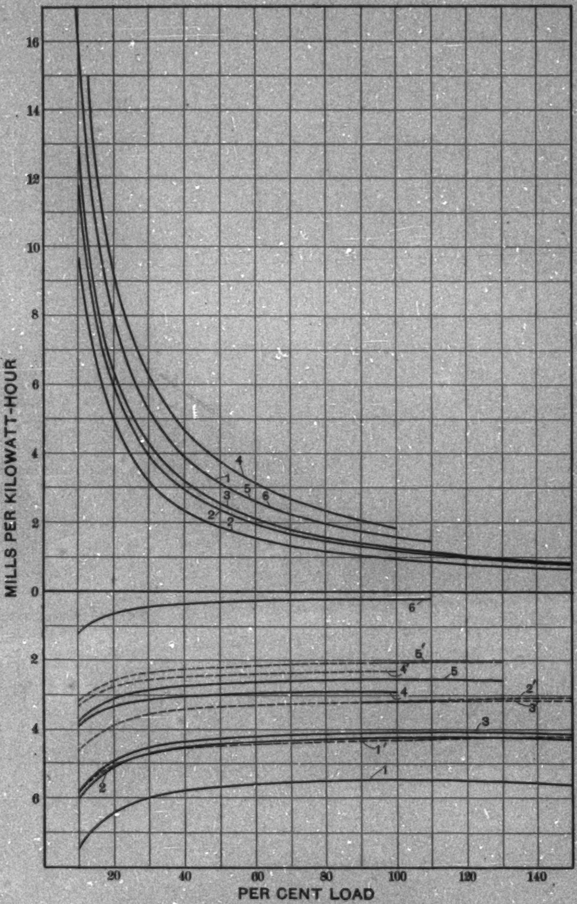

Fig. 21.—Summary of Figs. 1 to 4 inclusive.
Curves 1 2, 3, 4, 5, and 6 same as Fig. 8.

in many cases to decide the question of local steam or gas plant versus long-distance transmission from an hydraulic plant.

Figs. 15 to 20 inclusive are calculated from Figs. 1 to 6, and

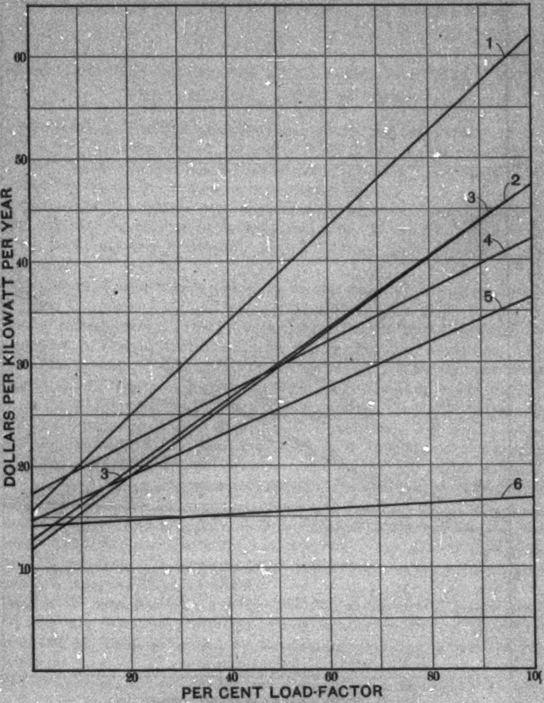

Fig. 22.—Summary of Figs. 15 to 20 inclusive.
Curves 1, 2, 3, 4, 5, and 6 same as Fig. 8.
Coal @ $3.00—14,500 B.t.u. per lb.

show the power-plant costs per kilowatt per annum for various load-factors for each of the six types of plants. Attention is called to the fact that the result shown in Fig. 20 is for power at the bus-bars only, and that this must of necessity be increased by the fixed charges and maintenance costs of the transmission lines and transformers.

In conclusion, the author trusts that the data presented in the

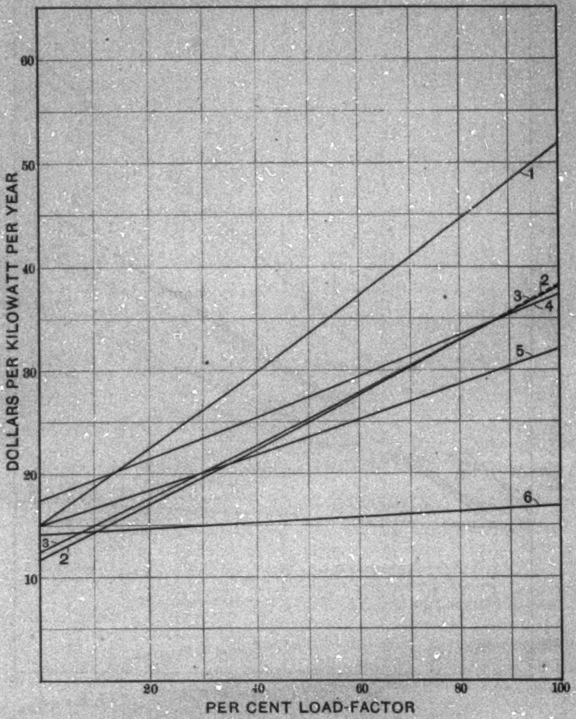

FIG. 23.—Summary of Figs. 15 to 20 inclusive.
Curves 1, 2, 3, 4, 5, and 6 same as Fig. 8.
Coal @ $1.50—11,000 B.t.u. per lb.

shape of 20 curves will be found useful in the preliminary work leading up to the design of a power plant to meet given conditions of load-factor and locality.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

REPORT OF THE BOARD OF DIRECTORS FOR THE FISCAL YEAR ENDING APRIL 30, 1909.

The Board of Directors presents herewith for the information of the membership its annual report, including brief references to the work of the various standing and special committees; also the usual statements showing the financial standing of the organization.

The Annual Convention was held at Atlantic City, June 29–July 2, 1908. The total registered attendance was 469. Thirty-five professional papers, including the President's annual address, were presented and discussed.

The Board of Directors has held 10 regular monthly meetings during the year.

On recommendation of the Finance Committee the Board directed the investment of certain Institute funds, during the year, as follows:

On June 1, 1908, of the cash surplus on deposit, drawing interest at the rate of 3%, there was invested in New York City 4½% bonds of 1957, par value $1,000 each, $10,950. On September 17, 1908, there was effected an exchange of eight $1,000 U. S. Government 3% bonds, value $8,107.50, for eight $1,000 New York City 4½% of 1917, purchase price $8,502.25. The difference in the respective values of the bonds, $394.75, was paid from the cash-surplus on deposit. On October 13, 1908, there was drawn from the International Electrical Congress Fund, the total amount of which was $2,333.07, drawing interest at the rate of 3%, the amount of $2,268, which amount was invested in two $1,000 New York City 4½% bonds of 1957, leaving a balance on deposit, in the International Electrical Congress Fund, of $65.07.

During the year the Institute By-laws were revised by a special committee of the Board of Directors, and were adopted by the Board on November 13, 1908, as revised by the committee, going into effect immediately.

Building Fund Committee.—The amount collected from subscribers during the year was $7,719.40. The interest on the bank balances amounted to $383.36. In addition to these amounts, $9,221.95 was refunded to the Building Fund for payments of interest on the mortgage during the period of occupancy of the building 25-33 West Thirty-ninth Street. These items make a total to the credit of the Building Fund during the year, of $17,324.71. (See financial statements at end of this report.)

Board of Examiners.—The Board held nine meetings during the year, and considered applications for election as Associates, enrolment as Students, and transfer to the grade of Member which were reported to the Board of Directors, as follows:

Recommended for election as Associates	916
Recommended for enrolment as Students	687
Recommended for transfer to the grade of Member	45
Not recommended for election as Associates	2
Not recommended for transfer to the grade of Member	20
Total number of cases considered	1,670

In accordance with the Constitution, Local Representatives of the Board of Examiners were appointed last fall, in various cities of the United States, Canada, and Mexico, to assist the Board in procuring information regarding applicants in their respective territories.

Sections Committee.—The reports of the secretaries of the Sections and Branches show a marked increase in the activity of the local organizations during the year. There are now 23 active Sections. A year ago there were 22 Sections, two of which, however, were inactive. Three new Sections were organized during the year, as follows:

Fort Wayne, Ind., authorized August 14, 1908.
Los Angeles, Cal., authorized May 19, 1908.
Madison, Wis., authorized January 8, 1909.

The Madison Section was formerly the University of Wisconsin Branch, and its change to a Section indicates increased interest in the local organization. In addition to the Section authorized, several meetings of local members have been held at Portland, Oregon and a petition from the Portland members for authority to organize a section has been received and will probably be acted upon at the May meeting of the Board of Directors.

There are 27 Branches, two of which were organized during the year, as follows: Case School, Cleveland, O., authorized January 8, 1909, and New Hampshire College, Durham, N. H., authorized February 19, 1909.

The increased activity of the Sections and Branches is indicated by the following brief summary made up from the reports received at the Secretary's office.

Sections.

	May 1, 1907 to April 30, 1908	May 1, 1908 to March 31, 1909	Increase over last year
Section meetings held	141	169	28
Original papers presented	120	167	47
Institute papers "	38	24	
Attendance	7,476	16,427	[8,951

Branches.

	May 1, 1907 to April 30, 1908	May 1, 1908 to March 31, 1909	Increase over last year
Branch meetings held	143	198	55
Original papers presented	84	158	74
Institute papers "	66	52	
Attendance	4,128	8,443	4,315

It will be noted from the above summary that the figures for 1908–1909 cover a period of only 11 months. This large increase is due in some measure to the coöperation of the local secretaries with the Institute office in sending in reports regularly, but more particularly to greater local interest and activity.

Standards Committee.—A meeting of this committee was held at Institute headquarters on December 10, 1908. It was decided to attempt no revision of the Standardization Rules during the present year. At the request of the U. S. National Committee of the International Electrotechnical Commission, certain questions on international nomenclature were considered.

International Electrotechnical Commission.—The U. S. National Committee of the International Electrotechnical Commission held a meeting on June 30, 1908, at Atlantic City on the occasion of the A.I.E.E. Convention.

A communication dated July 15, 1908, was received from the French committee, at the instance of the Bureau of Standards, proposing an international candle. The endorsement of this proposal was obtained from the members of the present U. S. committee and reported to the General Secretary in London, on September 25, 1908. The council meeting of the commission was held in London, on October 19, 1908. At this meeting Professor Elihu Thomson was unanimously elected President of the commission, to succeed the late Lord Kelvin. Certain modifications were adopted in the rules of the commission. It was voted that the commission should undertake to prepare a glossary of important international terms. The proposal of the French committee in regard to an international candle was laid over for consideration by the national committees. It was agreed that in future all measurements used by the commission should be expressed in terms of the metric system, with equivalents in parentheses when desired. A proposal has been received from the British committee to adopt an international candle = 10/9 of a hefner = 0.104 carcel = 1 bougie decimale = 1 pentane candle. This would place the American, British and French candles on a parity, to be maintained by the national standardizing laboratories of those countries. It involves a reduction of 1.6% of the unit of candle-power heretofore maintained by the Bureau of Standards. The proposal has been endorsed by the Bureau of Standards and all of the members of the U. S. committee. The 1.6% change in candle-power has been approved by the American Institute of Electrical Engineers, the American Gas Institute, and the Illuminating Engineering Society. National committees of the commission now exist, in addition to the United States; in Canada, Mexico, Great Britain, Germany, France, Hungary, Belgium, Italy, Spain, Sweden, Denmark and Brazil.

Library Committee.—We submit herewith our report for the year ending April 30, 1909, covering the growth and operation of the library and a statement of the present condition of the various library funds, and of the expenditures for the year.

The gifts to the library during the year reach a total of 273 volumes and pamphlets, while the additions by purchase were 335 volumes and by exchange 201 volumes, making a total of 809 accessions. At the time of the last annual report the library has just received some large additions that had not yet been entered on the library records. From these additions 492 volumes and pamphlets have been acquired making the total increase over the report of one year ago 1301 volumes and pamphlets. The total valuation now placed on the library and the increase for the year is shown in the table of library statistics.

The complete list of donors with the number of volumes presented by each is as follows:

DONORS

ADAMS, E. D	6
ALLGEMEINS ELEKTRICITATS GESELLSCHAFT	1
AMERICAN BELL TELEPHONE COMPANY	2
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS	2
AMERICAN STREET RAILWAY ASSOCIATION	8
BOSTON TRANSIT COMMMISSION	4
BUREAU OF RAILWAY NEWS	1
CALDWELL, EDWARD	68
CARBO, L. A	2
CARNEGIE TECHNICAL SCHOOL	1
CENTRAL ELECTRIC COMPANY	1
CHICAGO DEPARTMENT OF PUBLIC WORKS	1
CLARK, MYRON C., PUBLISHING COMPANY	1
CLAYTON, W. B. & CRAIG, J. U	1
CONNECTICUT BOARD OF ELECTRICAL COMMISSIONERS	1
DIXON CRUCIBLE COMPANY	1
ELECTRIC JOURNAL	1
ENGINEERS SOCIETY, UNIVERSITY OF MINNESOTA	1
FOSTER, H. A	2
FRENCH, MRS. E. D	1
GAS ENGINE	2
GENERAL ELECTRIC COMPANY	1
HERING, CARL	1
INTERNATIONAL ASSOCIATION OF MUNICIPAL ELECTRICIANS	1
IOWA ENGINEERING SOCIETY	3
IRON AGE	1
KANSAS GAS ASSOCIATION	1
McGRAW PUBLISHING COMPANY	55
MACMILLAN COMPANY	2
MAILLOUX, C. O.	25
MARTIN, T. C	7
MASSACHUSETTS GAS COMMISSION	1
MASSACHUSETTS GAS & ELECTRIC LIGHT ASSOCIATION	1
MICHIGAN ELECTRICAL ASSOCIATION	5
MUNICIPAL OWNERSHIP PUBLISHING COMPANY	1
NEW JERSEY COMMISSIONER OF PUBLIC ROADS	1
NEW YORK COMMISSIONER OF ACCOUNTS	1
NEW YORK STATE COMMISSION OF GAS & ELECTRICITY	1
NEW YORK STATE LIBRARY	1
NEW YORK STATE PUBLIC SERVICE COMMISSION, FIRST DISTRICT	1
NEW YORK STATE PUBLIC SERVICE COMMISSION, SECOND DISTRICT	4
NEW YORK STREET RAILROAD ASSOCIATION	1
NEW YORK STATE WATER SUPPLY COMMISSION	1

NEW YORK UNIVERSITY (SENATE)	1
OHIO ELECTRIC LIGHT ASSOCIATION	1
PENNSYLVANIA STATE BOARD OF AGRICULTURE	1
PERTIG, W	1
POOLE, C. E	1
ROEBLING'S SONS COMPANY	1
ROEDDER, O. C	1
ROSENTHAL, L. U	1
SNOW, W. B	5
SPRINGER, J	1
STONE & WEBSTER	6
THOMPSON, S. P	2
TORONTO, (CITY ENGINEER)	1
UNDERWRITERS LABORATORY	1
UNIVERSITY OF WASHINGTON	1
VAIL, T. N	1
VAN NOSTRAND COMPANY	10
WEAVER, W. D	1
WESTERN SOCIETY OF ENGINEERS	1
WILEY, JOHN & SONS	1
DONORS UNKNOWN	9

Other Accessions:

Purchases	335
Exchanges	201
Back Accessions	492
Total Accessions	1301

During the year a reorganization of the library staff and the general administration of the library has been effected. At a meeting of the Trustees of the United Engineering Society held on June 4, 1908, the following plan for the administration of the library was recommended to the governing bodies of the three founder societies:

First: That the administration of the library be placed in the hands of a chief librarian, all employes in the library to be subject to the direction of said chief librarian. It was agreed that Miss L. E. Howard should be appointed chief librarian, her present yearly compensation to be increased $200 in this connection.

Second: That each new employe in the library shall be approved both by the authorized representative of the founder societies interested, and by the chief librarian.

Third: In the event of any employe not being satisfactory to said representative of the founder society interested, or to the chief librarian, the fact shall be reported by the chief librarian to the House Committee, which shall have the power to act.

Fourth: That in the absence of the chief librarian the House Committee shall have the right to specify an employe of the library to act as chief librarian during such period of absence.

Fifth: That the United Engineering Society be requested to pay the salaries of all the library employes, and the amount to be repaid by the founder societies respectively shall be distributed in such proportion as may be jointly agreed upon.

At the meeting of the Institute Directors held on Friday June 12, 1908, the above recommendations were approved, to take effect July 1, 1908. These recommendations were also approved by the American Society of Mechanical Engineers and the American Institute of Mining Engineers, and since July 1, 1908, the library staff has been in charge of Miss Howard. Previously to that date each library had its own librarian with an assistant working independently of the others. The new arrangement has proved to be entirely satisfactory and a decided improvement over the previous method of operation.

The following tabulations give the state of the five funds from which the Library Committee is entitled to draw·

DONATIONS (GENERAL LIBRARY FUND)

Dr.		Cr.	
Balance May 1, 1908	$244.15		
Interest May 1, 1909	7.36	Unexpended	$251.51
	$251.51		$251.51

CARNEGIE FUND

Balance May 1, 1908	3,168.19		
Interest	88.72	Wheeler Bibliography	3,256.91
	$3,256.91		$3,256.91

MAILLOUX ENDOWMENT FUND ($1,000)

(Proceeds for the maintenance of certain sets of periodical publications)

Balance May 1, 1908	$ 17.35	Subscriptions	$ 17.00
Interest May 1, 1909	30.00	Unexpended	30.35
	$ 47.35		$ 47.35

INTERNATIONAL ELECTRICAL CONGRESS OF ST. LOUIS, 1904 FUND

Principal, May 1, 1908	$2,146.12		
Additions to Fund	121.88		
Invested in New York City 4½% Bonds	$2,268.00		
Interest May 1, 1909		Unexpended	$124.72

WEAVER FUND

Balance May 1, 1908	$ 75.00	Expended	$ 9.56
		Unexpended	65.44
	$ 75.00		$ 75.00

INSTITUTE APPROPRIATION ACCOUNT

Dr.		Cr	
Appropriation for maintenance for year ending October 1, 1909	$3,000.00	Librrian and assistants	$1,250.68
		Cataloging	199.17
		Desk attendant	68.01
		Insurance	88.79
		Binding	247.75
		Supplies	51.69
		Subscription	89.25
		Books	397.12
		Typewriter	15.70
		Printing	17.66
		Book plates	24.50
		Miscellaneous	10.27
		Unexpended	539.41
	$3,000.00		$3 000 00

The general statistics of the Library and its valuation are shown in the following tabulation:

STATISTICS OF LIBRARY, MAY 1, 1909

Source	Titles	Volumes	Pamphlets	Valuations
Report of May 1, 1908	7,976	11,828	565	$23,406.55
PURCHASES:				
Mailloux Fund	4	8		17.00
Weaver Fund	8	10		9.65
Institute Appropriation	120	174		397.12
Periodicals	170	218		436.00
Gifts and Exchanges		1,277		300.00
Totals	8,278	13,515	565	$24,566.23
Duplicates	501	714		900.00

In the following table are given the figures for the total valuation of the library property:

Books	$24,566.23
Stacks	1,761.05
Furniture, Catalogue Cases, etc	208.28
	$26,535.56

LIBRARY ATTENDANCE

		Day	Evening
May,	1908	400	196
June	"	419	136
July	"	441	Closed
August	"	362	Closed
September	"	393	125
October	"	381	180
November	"	425	200
December	"	520	441
January	1909	485	250
February	"	533	254
March	"	535	280
April	"	529	219
Totals		5,423	2,281
Total day and evening			7,704

IMPORTANT GIFTS AND ACCESSIONS

Mr. Edward D. Adams has continued his special interest in the library and has donated as heretofore the yearly *Proceedings* and *Transactions* of the Royal Society of London, and the additional volumes of the International Catalogue of Scientific Literature. He has also borne the expense of binding the volumes of the catalogue heretofore added to the library. The fund of $1000, known as the " C. O. Mailloux Fund," has again been drawn upon for the subscription price of the four important periodical sets originally presented by Mr. Mailloux to the library. The proceeds of the International Congress Fund, which is now invested so as to yield an annual income of nearly $100, has been drawn upon for the very recent purchase of several reports of international congresses and international electrical exhibitions. The Public Service Commission of the Second District, State of New York has presented a set of its publications. Some incomplete sets have been entirely or nearly completed, and a complete set of "Terrestrial Magnetism" has been added. The principal purchases have been publications of recent years.

GENERAL INVENTORY AND INSPECTION

This work which was in progress at the time of the last annual report has been continued and completed. The errors and deficiencies discovered have been corrected by the present librarian and the entire collection thus put into excellent shape for the preparation of the union card catalogue.

THE UNION CARD CATALOGUE

Early in the year it was decided to prepare a union card catalogue of all the books belonging to the three founder societies. For this purpose an expert cataloger was employed and the work has progressed so rapidly that the catalogue is already completed. A new card cabinet of 180 drawers with a capacity for nearly 200,000 cards has been installed in the general library and the union catalogue is now in public use.

TRADE CATALOGUES

A new feature of the library is the file of trade and manufacturers' catalogues. These are arranged in the drawers of a vertical file and are indexed both by names and subjects. As new editions of catalogues are received the old ones are displaced.

THE ENGINEERING INDEX

An effort has been made to have available for the use of searchers every general index to engineering literature, and the library now has a fine collection of such reference books. These include Kerl's *Repertorium*, The Royal Society's *Catalogue of Scientific Papers* and its successor, the *International Catalogue of Scientific Literature*, both of which were the gift of Mr. Edward D. Adams; a complete set of the *Engineering Index*, a complete set of *Science Abstracts*; and many other valuable helps. Reference to the *Engineering Index* is facilitated by clipping each monthly issue as it appears and arranging the titles on cards which are then arranged in a subject classification for the use of the public. This index is thus kept up to date as closely as possible. The publishers of the *Electrical World* have just contributed a complete set of its semi-annual indexes, specially bound with thumb index tabs, making a very handy and serviceable volume.

TELEPHONE RECORDS

The very vaulable set of telephone records presented to the library by the American Bell Telephone Company, and comprising about 100 volumes, is now being catalogued in detail. Each volume contains many pamphlets and other material, either printed or in manuscript form, and it is hoped that the catalogue when completed may be printed by the Institute so that the contents of this vaulable set may be made available for more general consultation.

HARMONIOUS OPERATION

We take pleasure in reporting that the authorities in charge of the libraries of the American Institute of Mining Engineers and the American Society of Mechanical Engineers have coöperated with us to bring about an efficient service under conditions that are not always the most favorable. The three libraries here housed together still remain under separate and independent ownership, but each has shown its desire to make the various collections as useful as possible to the members of all societies alike as well as to the general public. A further movement in this direction is now under way, and a recommendation that each society print and circulate to all members alike the accessions of all three libraries is now being considered by each society.

HISTORICAL MUSEUM

While we have not actively pushed the affairs of the Historical Museum which was established about three years ago the matter has had our attention from time to time. At present there seems especially to be no satisfactory space at our disposal for the proper carrying out of the original plan. The space originally set aside on the twelfth floor has been required for library purposes during the past year and with the increase in the library this condition will no doubt continue. The project however is one that is important and deserves some more adequate provision for the preservation and display of historical apparatus.

Respectfully submitted,

The Library Committee,
EDWARD CALDWELL,
Chairman,
W. G. CARLTON.
H. E. CLIFFORD.
MAX LOEWENTHAL.
PHILIP TORCHIO.

Committee on Intermediate Grade of Membership.—The committee has considered along broad lines the question of the need and practicability of adding one or more grades of membership to those now existing It has examined the classification of other organizations having various grades of membership. The subject has proved an extremely difficult one, involving, as it does, general policy, as well as a large amount of detail. The committee is now formulating its views in regard to the various points involved, and will probably suggest that its report be printed in the PROCEEDINGS, and the views of the membership in regard to the subject be invited.

Committee on Bibliography.—This committee has completed its work upon the catalogue of the Wheeler Gift of Books, Pamphlets and Periodicals. The catalogue has been published in two volumes and is now being distributed.

Meetings and Papers Committee.—During the past year this committee arranged for eight regular and two special meetings. Nine papers were presented at the eight regular meetings. One of the special meetings was devoted to the subject of conservation of natural resources, and the other to industrial education. The efforts of the committee, throughout the year, have been directed towards securing a single paper of unusual merit for each regular meeting. The subjects were selected so as to cover as fully as possible the broad field of electrical engineering, in order to appeal to the diversified membership. The several sub-committees of the Meetings and Papers Committee have been utilized during the year to supply papers and discussions on their special subjects, with gratifying results.

Educational Committee.—The committee held two meetings during the winter, in New York City, at which the scope of the work was discussed and plans were made for two special meetings of the Institute. At the outset it was decided that as technical education had been treated exclusively during the preceding year, industrial training should be adopted, as the topic for the current year. As a part of this plan a special meeting of the Institute was held in New York, under the auspices of the committee, on April 16, 1909. As a further part of the plan, a special session of the 1909 Convention will be occupied with papers and discussions on the general subject of industrial education. In addition to the preparations for the meetings mentioned, the committee has carefully considered a plan for holding examinations throughout the country, under the auspices of the Institute. The committee has also considered a plan for assisting in research work throughout the country, by compiling lists of suitable subjects for investigation.

High-Tension Transmission Committee.—The Institute has held one meeting under the auspices of this committee, on April 9, 1909. Two papers were presented and discussed at this meeting, and there were conducted on the stage of the auditorium some tests of terminals at voltages up to 250,000. It is contemplated that at least one session at the annual convention will be under the auspices of this committee.

Committee on Industrial Power.—A number of meetings of this committee have been held during the year. Nearly all of the Sections have held meetings devoted to the subject of industrial power, as a result of the efforts of the committee. It was hoped that the papers presented at these meetings could be collected and published in book form, but it was found impossible. It may be possible, however, to do this next year. The regular March meeting of the Institute was devoted to the subject of industrial power. It is planned to devote one of the sessions of the annual convention to this subject.

Editing Committee.—Since September, 1908, there have been edited and published eight numbers of the PROCEEDINGS. The total number of pages of these PROCEEDINGS is 1701; of this total, 304 pages have appeared in Section I; 767 pages in Section II. Of the 767 pages in Section II, 354 pages were devoted to technical papers and 413 pages to discussions.

Vol. XXVII, of the TRANSACTIONS, consisting of the papers, and discussions during the calendar year 1908, the report of the Board of Directors for the fiscal year ending April 30, 1908, and the By-Laws, contains 1716 pages. Vol. XXVII will be issued in two parts. Part I, consisting of 858 pages, will contain the papers and discussions presented between January 1, 1908, and the end of the morning session on June 30, 1908, at the Annual Convention at Atlantic City, the report of the Board of Directors, and the By-Laws. Part II, also consisting of 858 pages, will contain the papers and discussions presented between the evening session on June 30, 1908, at the Atlantic City Convention, and December 31, 1908. The volume will probably be ready for distribution about August 1, 1909.

The chairman of the Editing Committee has given personal attention to all the MSS., of the papers and discussions at the Institute Sections and Branches that have been forwarded to the Secretary's office during the present administration. Thirty-six MSS., of this nature have been received and passed upon. These MSS., consisted of approximately 700 pages of typewritten matter.

Law Committee.—The Law Committee considered and reported upon various questions submitted to it by the Board of Directors during the past year, the most important matter being the advisability of drafting by-laws to govern the actions of the Meetings and Papers, and Editing committees. After careful consideration of the subject it was the unanimous opinion of the committee that the conditions governing the acceptance of papers and discussions were so varied as to make it impossible to draft any rigid rules for the guidance of those committees, and that the present right of appeal to the Board of Directors, which any member now has, was a sufficient safeguard of the rights of all members.

Code Committee.—The Code Committee has held a number of meetings during the year. The most important matter that has been considered was in connection with Rule 13-A of the Board of Fire Underwriters. This rule deals with the grounding of secondary circuits. The committee agreed that the rule should be made mandatory up to and including 150 volts between any wire and ground, and optional up to and including 250 volts between any wire and ground. This resolution was handed to the president of the National Conference on Electrical Rules. Final action on the resolution was deferred, pending an arrangement for a meeting of the Code Committee with a committee of the National Board of Fire Underwriters.

Committee on Conservation of Natural Resources.—During the past year the Committee on Natural Resources has carried on correspondence and held informal conferences with representatives of the U. S. Government and with other societies, looking to the furtherance of the legitimate object of the conservation movement. The committee also originated the movement which resulted in a very successful joint meeting held March 24, 1909, under the auspices of the four national engineering societies. The committee feels that two extremely valuable objects were gained in this joint meeting: 1. The presentation of the engineers' views on the conservation movement. 2. Bringing the four societies to act jointly on this subject, which establishes a precedent for similar action on other important subjects of common interest to all, and has a tendency to promote cordial relations between the societies.

Edison Medal Committee.—Before the new deed, entitled "Amended and Substitute Deed of Gift Creating the Edison Medal", was executed, on March 26, 1908, five graduate students from institutions of learning, duly qualified to compete for the Edison Medal under the old deed, had submitted theses in competition for the medal for 1907. These students, at the request of the Institute, withdrew from competition for the medal, and resubmitted their theses in a special competition for a Diploma of Merit, plus a cash award of $150.00. A sub-committee of the Edison Medal Committee reported to the chairman on May 8, 1909, its recommendation in respect to the award of the student theses, which will be acted upon at a meeting of the Edison Medal Committee on May 18.

Revision of the by-laws of the Edison Medal Committee was begun in October, 1908, and a final draft as approved by the committee was presented to the Board of Directors on December 11, 1908.

John Fritz Medal.—The John Fritz Medal Board of Award upon which the Institute is represented arranged for a meeting which was held on April 13 at which the medal for 1909 was presented to Mr. Charles T. Porter, for meritorious service in the advancement of steam engineering. Four addresses were made at this meeting by representatives of the four national engineering societies.

Increase of Membership Committee.—This committee has held several meetings during the year, and has sent out numerous letters and circulars. A special effort was made to interest engineers in the U. S. Army and Navy. During the year ending May 1, 1909, 1079 applications for membership were received—almost as many as were received during each of the two preceding years.

Membership. The present total membership and the increase during the past year are indicated below:

	Hon. Mem.	Mem.	Assoc.	Total
Membership, April 30, 1908	1	573	5,100	5,674
Additions:				
New Associates			1,005	
Transferred		53		
Deductions:				
Died		4	13	
Resigned		4	66	
Dropped		11	181	
Transferred			53	
Membership April 30, 1909	1	607	5,792	6,400

Net increase during the year in membership........................726

Resignations.—The following Members and Associates have resigned during the year in good standing.

Members.—F. W. Brady, J. W. Swinburne, C. H. Wilmerding, C. H. Wordingham.

Associates.—J. C. T. Baldwin, R. J. Barker, B. H. Bendheim, E. R. Berry, R. H. Black, A. E. Blondel, C. A. Bramhall, A. U. Brandt, J. Brayshaw, W. S. Brewster, A. J. Brown, W. D. Brown, Leonard Carpenter, M. E. Chester, A. S. Clift, B. W. Cooper, W. R. Cooper, W. W. Dean, B. M. Drake, Edward Durant, C. D. Ehret, Albert Esling, E. E. Ferrin, W. S. Ford, M. J. Francisco, J. B. Edwards, E. E. Gage, H. L. Gilbert, Leon Goldsmith, W. M. Haddock, C. G. Halleck, W. L. Hildburg, Christopher Hoff, Jr., B. K. Hough, James C. Howe, W. McA. Johnson, Henry Kaetker, P. H. Knight, F. N. Koziell, P. J. Kreusi, F. F. Lee, Norman Leeds, C. H. Machen, Benjamin Magnus, B. F. Mechling, Jr., L. G. E. Morse, M. M. Neurath, M. L. Norris, R. B. Parrott, Carroll Potter, J. D. Ross, E. H. Rupe, R. A. Scott, T. G. Seidell, A. B. Skelding, W. W. Sloane, W. Stuart Smith, A. B. Stetson, F. K. P. Stilwell, Julius Strauss, S. Tada, J. C. Van Buren, W. M. Venable, S. T. Wellman, Charles West, J. M. Zapata.

Total resignations, 70.

Deaths.—The following deaths have occurred during the year:

Members.—W. A. Anthony, E. V. Baillard, C. E. Gifford, F. A. C. Perrine.

Associates.—H. C. Buck, A. M. Bullard, W. H. Cordell, Theodore Dimon, E. G. Eberhardt, A. B. Elliott, Otto Holz, J. M. Mahoney, W. S. Scarlett, E. F. Schaefer, Paul von Lehoczky, F. G. Warman, E. L. Zalinski.

Total deaths, 17.

Delinquent.—Dropped as delinquent during the year, 192.

The average receipts and disbursements *per capita* for the past seven years, are shown in the following table:

RECEIPTS AND DISBURSEMENTS PER YEAR PER MEMBER.

During each fiscal year for the past seven years.

Year	1903	1904	1905	1906	1907	1908	1909
Membership, April 30th, each year	2230	3027	3460	3870	4521	5674	6400
RECEIPTS PER MEMBER:							
Entrance Fees	$1.59	$1.65	$0.83	$0.75	$0.90	$1.21	$0.79
Dues	9.01	9.33	9.30	9.47	8.95	9.36	10.19
Transactions, Sales, Advertising	1.79	2.11	1.70	2.15	1.81	1.83	1.68
Badges	.35	.39	.28	.27	.30	.43	.32
Interest	.21	.18	.21	.13	.25	.18	.23
	$12.95	$13.66	$12.32	$12.77	$12.21	$13.01	$13.21
DISBURSEMENTS PER MEMBER:							
Transactions	$4.67	$3.48	$3.77	$3.33	$2.83	$3.51	$3.65
Salaries	2.49	2.50	2.20	2.64	2.53	2.55	1.93
Meeting Expenses, incl. Sections	.87	1.16	.82	.68	.68	.91	.84
Housing	.65	.79	.75	.68	1.33	1.15	.96
Library, incl. Salaries	1.38	1.39	.81	.69	1.37	.51	.39
Postage	.69	.66	.66	.58	.59	.65	.74
Stationery and Miscel. Printing	.96	1.01	.70	.78	.85	.80	.82
General Expenses	.52	.45	.54	.29	.43	.62	.29
Badges	.27	.35	.25	.22	.29	.40	.28
Express	.15	.28	.22	.23	.28	.14	.23
Advertising				.36	.30	.35	.27
Office Fittings					.14	.14	.09
Total	$12.65	$12.02	$10.72	$10.48	$11.62	$11.73	$10.49
Credit Balance per Member	$0.30	$1.64	$1.60	$2.29	.59	1.28	2.72

LAND, BUILDING AND ENDOWMENT FUND.

Receipts.		Disbursements.	
Before appointment of committee	$ 6,100.00	Paid United Engineering Society, acct. of contract	$ 8,000.00
Collected by Committee	143,328.90	Paid United Engineering Society, acct. of mortgage	99,000.00
Interest on balances	5,381.76	Paid United Engineering Society, acct. of interest	19,529.45
Reimbursement by Institute	9,221.95	Expenses of Committee	10,440.73
		Balance in bank, May 1, 1909	27,062.43
Total	$164,032.61	Total	$164,032.61

New York May 18, 1909.

MR. LOUIS A. FERGUSON,
President American Institute of Electrical Engineers,
No. 33 West Thirty-ninth Street, New York.

Dear Sir: During the past year your Finance Committee has performed its prescribed duties as provided for in the Constitution and By-laws. We respectfully submit herewith the report of the chartered accountants, Messrs. Peirce, Struss & Company, who have audited the books of the Institute for the year.

Your committee, in company with the Secretary and a representative of the chartered accountants, has examined the securities held by the Institute, and finds them to be as stated in the balance sheet.

In preparing the annual statement this year, the chartered accountants have followed previous practice in omitting from the assets and from the liabilities, any accruals of interest, but we recommend that the Board of Directors instruct that in future statements these accruals be entered on both sides of the balance sheet.

Similarly, the item of Office Furniture and Fixtures is this year set up at its present appraised value, such value being determined by a recent re-appraisal. We recommend that the Board of Directors direct the furniture account to be set up at its full cost value, to which shall be added each year the cost of additional furniture which may be purchased from time to time; that as against this amount a reserve liability fund be created, to which shall be added annually a sum equivalent to a suitable per cent of the total furniture account, such reserve fund to be held against possible replacement of furniture and fittings.

You will note the sum of $9,921.95 entered as a reimbursement of the Land, Building and Endowment Fund, which amount is deducted from the year's surplus. In explanation of this item it seems proper to state that by authorization of the Board of Directors, all payments of interest on the unpaid balance of the cost of land since the Institute has occupied its present quarters, have been adjudged a current expense payable from the Institute current income, and inasmuch as certain sums for this purpose had previously been paid out of the Land, Building and Endowment Fund, an equivalent amount with all interest received on same has been restored to that fund, which accounts for the item referred to.

Respectfully submitted,

CALVERT TOWNLEY,
Chairman Finance Committee.

New York, May 11, 1909.

MR. CALVERT TOWNLEY,
Chairman Committee on Finance.

Dear Sir: In accordance with your instructions, we have audited the books and accounts of the American Institute of Electrical Engineers, for the year ended April 30th, 1909.

The results of this examination are presented in four exhibits, attached hereto, as follows:—

Exhibit A. Balance Sheet, April 30th, 1909.

Exhibit B. Receipts and Disbursements for general purposes for year ended April 30, 1909.

Exhibit C. Receipts and Donations for designated purposes, also expenditures for year ended April 30, 1909.

Exhibit D. Condensed Cash Statement.

We beg to present attached hereto our certificate to the aforesaid exhibits.

Yours very truly,
(Signed) PEIRCE, STRUSS & CO.
Certified Public Accoutants.

New York, May 11, 1909.

MR. CALVERT TOWNLEY,
Chairman Committee on Finance.

Dear Sir: Having audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1909, we hereby certify that the accompanying Balance Sheet is a true exhibit of its financial condition as of April 30, 1909, and that the accompanying statements of Cash Receipts and Disbursements are correct.

(Signed) PEIRCE, STRUSS & CO.
Certified Public Accountants.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

BALANCE SHEET, APRIL 30, 1909.

EXHIBIT A.

ASSETS.		
CASH:		
Land, Building and Endowment fund	$27,062.43	
General Library fund	251.51	
Compounded Membership fund	5,355.57	
*Mailloux fund	1,000.00	
		33,669.51
†General cash in bank	9,198.65	
Secretary's petty cash on hand	500.00	
		9,698.65
International Electrical Congress of St. Louis, 1904, Library fund Bonds	2,268.00	
		2,268.00
New York City 4½% Gold Bonds	30,000.00	
Premium on Bonds	1,952.50	
		31,952.50
Westinghouse Elec. & Mfg. Co's stock		50.00
Equity in Societies Building (25 to 33 West 39th Street)	353,346.61	
One-third cost of land (25 to 33 West 39th Street)	180,000.00	
		533,346.61
Library volumes and fixtures	26,644.67	
Transactions	5,480.25	
Office furniture and fixtures	5,139.75	
Works of art, paintings, etc	2,300.00	
Badges	495.30	
		40,059.97
ACCOUNTS RECEIVABLE:		
Members for past dues suspense acct.	11,283.75	
Members for entrance fees	265.00	
Miscellaneous	478.51	
For advertising	1,762.00	
		13,789.26
Total Assets		$664,834.50

LIABILITIES AND SURPLUS.		
FUNDS		
Land, Building and Endowment Fund	$27,062.43	
General Library Fund	251.51	
Compounded Membership Fund	5,355.57	
Mailloux Fund	1,000.35	
International Electrical Congress of St. Louis, 1904, Library Fund:		
Principal	2,268.00	
Unexpended Income	124.72	
Accounts Payable subject to approval by Finance Committee	4,035.38	
		40,097.96
United Engineering Society (for cost of land)		81,000.00
Total liabilities.		$121,097.96
SURPLUS:		
In cash	9,573.58	
New York City bonds	31,952.50	
In property and accounts receivable.	502,210.46	
		543,736.54
Total liabilities and surplus		$664,834.50

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* The Farmers' Loan and Trust Co. deposit account includes 35c. of the Mailloux Fund.

† $65.44 of the Weaver donation.

$124.72 of Int. Elec. Congress of St. Louis Library Fund.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DISBURSEMENTS FOR GENERAL PURPOSES FOR YEAR ENDED APRIL 30, 1909.

EXHIBIT B.

RECEIPTS.		
Entrance Fees	$5,025.00	
Current Dues	54,759.50	
Past Dues	5,726.00	
Advance Dues	290.50	
Students' Dues	3,957.00	
Transfer Fees	480.00	
Badges	2,084.50	
		$72,322.50
Sales, Transactions, etc.	1,787.26	
Subscriptions, Proceedings	1,439.76	
Advertising	7,228.89	
Binding	137.25	
Exchange	28.21	
Library Sales	114.29	
INTEREST:		
Bonds	977.07	
Bank Balances	512.22	
		$12,224.95
Total		$84,547.45

DISBURSEMENTS.		
Stationery and Printing	4,766.10	
Postage	4,706.43	
General Expenses	1,887.79	
Meeting Expenses	1,960.60	
Section Meetings	3,389.54	
Badges	1,824.05	
Salaries	9,964.00	
Bibliography	485.05	
Office Furniture	546.90	
		$29,530.46
PROCEEDINGS—TRANSACTIONS:		
Printing	16,009.84	
Salary	2,400.00	
Engraving	1,261.10	
Volumes	3,294.57	
Electrotyping	1,023.49	
Binding	1,787.07	
Express	1,475.25	
Advertising Commissions	1,714.27	
		$28,965.59
LIBRARY:		
Librarian & Asst's.	$1,250.68	
Cataloguing	199.17	
Desk Attendant	68.01	
Insurance	88.79	
Binding	247.75	
Supplies	51.69	
Subscription	89.25	
Books	397.12	
Typewriter	15.70	
Printing	17.66	
Book plates	24.50	
Miscellaneous	10.27	
		$2,460.59
United Engineering Society Assessments (Rent)		$6,166.68
Total		$67,123.32
Excess receipts over disbursements		17,424.13
		$84,547.45
To Surplus—as above		17,424.13
Reimbursement of Land Building and Endowment Fund		9,221.95
Net to surplus		$8,202.18

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

RECEIPTS AND DONATIONS FOR DESIGNATED PURPOSES, ALSO EXPENDITURES FOR YEAR ENDED APRIL 30, 1909.

EXHIBIT C.

RECEIPTS.	
Land, Building and Endowment fund, Donations, Interest, etc.	$17,324.71
Carnegie (Library) Fund, Interest	88.72
General Library Fund, Interest	7.36
Compounded Membership Fund, Interest	195.57
International Electrical Congress of St. Louis, 1904, Library Fund, on account of Principal	31.10
International Electrical Congress of St. Louis, 1904, Library Fund, on account of interest	108.28
	$17,755.74
Mailloux Fund Interest ($30.00) received after April 30th 1909	
EXPENDITURES.	
Land, Building and Endowment Fund, on account of Interest and Expense	$3,610.59
Carnegie (Library) Fund	3,256.91
Compounded Membership Fund	440.00
Mailloux Fund	17.00
Weaver Donation	9.56
International Electrical Congress of St. Louis, 1904, Library Fund for Bonds	2,268.00
Total Expenditures	9,602.06
Excess of Receipts over Expenditure	8,153.68
	$17,755.74

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS.

CONDENSED CASH STATEMENT.

EXHIBIT D.

Cash on deposit April 30th 1908	$37,857.05	
Secretary's petty cash, April 30th, 1908	500.00	
	$38,357.05	
Receipts for general purposes, Exhibit "B"	84,547.45	
Receipts for designated purposes, Exhibit "C"	17,755.74	
		$140,660.24
Disbursements for general purposes, Exhibit "B"	67,123.32	
Expenditures for designated purposes, Exhibit "C"	9,602.06	
Expended for New York City 4½% Bonds	11,344.75	
Reimbursement of Land Building and Endowment Fund	9,221.95	
		97,292.08
Balance on hand, April 30th, 1909		43,368.16
On deposit for designated purposes, Exhibit "A"	33,669.51	
On deposit for general purposes, Exhibit "A"	9,198.65	
Secretary's petty cash, Exhibit "A"	500.00	
		$43,368.16

PROPERTY ACQUIRED DURING THE YEAR.

Office Furniture and Fixtures	$546.90
Library Books and Binding	644.87

Respectfully submitted for the Board of Directors.

RALPH W. POPE, *Secretary.*

New York, May 18, 1909.